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PROPERTIES OF STATES OF NEON 21 FROM
 $O^{18}(\alpha, n\gamma)Ne^{21}$

by

JOHN GREGORY PRONKO

A THESIS

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UNIVERSITY OF ALBERTA
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled PROPERTIES OF STATES OF NEON 21 FROM $O^{18}(\alpha, n\gamma)Ne^{21}$, submitted by John Gregory Pronko in partial fulfilment of the requirements for the degree of Doctor of Philosophy.

Date

February 15, 1965

ABSTRACT

Spectroscopic parameters of Ne^{21} were measured using the reaction $\text{O}^{18}(\alpha n\gamma)\text{Ne}^{21}$. The method of triple angular correlations was used to determine the spins of the 0.35 MeV, and 1.75 MeV and 2.87 MeV levels as well as the multipole mixing ratios of the gamma rays emitted from these states. The target used was approximately 20 keV thick at 2.50 MeV and consisted of isotopically separated O^{18} . At a bombarding energy of 4.43 MeV the gamma rays from the 0.35 MeV and 1.75 MeV levels were observed and three types of correlation experiments performed, neutron-gamma ray angular correlations with the neutron counter at zero degrees, gamma distributions with the intermediate radiation unobserved, and gamma-gamma correlations. These yielded spin assignments of 5/2 and 7/2 for the 0.35 MeV and 1.75 MeV levels respectively and multipole mixing ratios for the gamma rays of $\delta_{0.35} = +0.08 \pm 0.02$, $\delta_{1.40} = +0.18 \pm 0.02$ and $\delta_{1.75} = +0.034 \pm 0.04$. The 1.75 MeV level was found to decay 4.6% to the ground state. At a bombarding energy of 5.50 MeV, neutron-gamma ray correlations yielded a spin of 9/2 as most probable for the 2.87 MeV level with $\delta_{1.12} = +0.13 \pm 0.06$ and $\delta_{2.52} = +0.035 \pm 0.045$. This level was found to decay at least 37% to the 1.75 MeV level.

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CHAPTER I. THEORY AND OBJECTIVES

1.1 Introduction

The subject of this thesis is the measurement of spectroscopic parameters of Neon 21 using the method of triple angular correlations. The need for these measurements arises from the fact that no experiment has been designed which will measure directly the forces involved in nuclear matter. Instead the physicist is concerned with the effects of these forces, which are the nuclear energy levels and their properties. By measuring these properties, the assumptions made concerning the nuclear force may be evaluated. These assumptions are contained in the Hamiltonian, which describes completely the nuclear model used.

In recent years there has been an increasing interest in the measurement of spectroscopic parameters of nuclei in the $1d-2s$ shell. This has been because of the success of some models in describing nucleon behavior of nuclei in this shell region. The ability of these models to explain this behavior is a step toward a unique theory of nuclear structure. However, before a complete theory can be developed more spectroscopic parameters must be measured. Neon 21 is a member of this group of nuclei for which the properties have been predicted by calculations based on different models. The success of the predictions can only be known after more measurements are made. To study

this nucleus the reaction $O^{18}(\alpha\gamma)Ne^{21}$ was chosen because of the ease of interpretation which is a consequence of both projectile and target having spin zero. The input channel spin is defined as the sum of the spins of the target nucleus and the bombarding particle, and therefore has only one possible value, zero, in this case.

The properties of the levels in Ne^{21} were studied using the method of triple angular correlations. The angular correlations of radiations emitted or absorbed successively in nuclear processes has been one of the principal tools available for the spectroscopy of excited states. Angular correlations are used in almost every branch of nuclear physics and are simply the relative intensities of outgoing radiation with respect to a polar direction θ . This intensity distribution is associated with the angular momenta and parities of nuclear states, that is with their symmetry properties under the operations of spatial rotation, spatial reflection, and time reversal. By the application of the general laws of invariance, the angular correlations can be calculated and compared with the experimental results. Thus, the physicist is provided with information concerning the spins and parities of nuclear states.

The original calculations performed by Myers (My 38) were limited in scope because of the absence of suitable algebraic procedures. Only the simplest type of reaction could be treated until Racah (Ra 42) developed the transformation theory for angular momenta. This provided the algebraic techniques used by many authors in the following years to

apply the theory to nuclear reactions. This period was followed by an excellent survey article written by Devons and Goldfarb (De 57) in which accounts of experiments, as well as a comprehensive review of the theory, are given. At the same time the calculations of the coefficients were simplified by the publication of tables which combine many of the coefficients into less complicated forms.

Litherland, Ferguson, McCallum, Gove and Batchelor (Li 60, Li 61, Ba 60) showed theoretically and demonstrated experimentally that the interpretation of triple angular correlations can be greatly simplified if suitable restrictions are imposed on the counter geometry and the reaction populating the states of interest. The problem is to effect the necessary restrictions on the magnetic substates so that a selection of aligned nuclear states is obtained for a given nuclear reaction. Litherland and Ferguson have shown that by using an axially symmetric detector located at zero degrees with respect to the beam, for the observation of the second radiation in coincidence with the third radiation, the intermediate state is effectively aligned. The magnetic substates selected in a level formed by the absorption of an unpolarized particle in the direction of the z-axis and followed by the emission of a second particle along the z-axis is dependent upon the spins of the target nucleus, bombarding particle and emergent particle. The magnetic quantum number of any substate that can be populated does not exceed the sum of these spins, since orbital angular momentum is always perpendicular to the direction of motion and in the

above case only the particles which are moving along the z-axis are considered. This means that spins are the only angular momenta with projections on this axis. If the target spin and projectile spin are zero, the magnetic substates populated are those with $m = \pm s$, where s is the spin of the emergent particle. For the $O^{18}(\alpha\gamma)Ne^{21}$ reaction, where the O^{18} nucleus has a spin of zero and the alpha particle has a spin of zero, the final states populated in the levels of Ne^{21} are $m = \pm 1/2$. If the orbital angular momentum of the neutron is zero, i.e. s-wave neutrons, the only substates populated are $m = \pm 1/2$ regardless of the direction of emergence of the neutron. This, of course, is a very special case and cannot be predicted with any certainty unless the intermediate spins are known.

Litherland and Ferguson (Li 61) have also shown that if polarization is not observed, the states are symmetrically populated, i.e. $P(m) = P(-m)$, where $P(m)$, the population parameter associated with the magnetic substate, m , is the relative probability that the substate is populated.

In the ideal case where the input channel spin is zero there is a possibility of populating magnetic substates greater than $m = \pm 1/2$ despite the fact that the counter is at zero degrees. This arises from the finite solid angle of the neutron counter; off axis particles are detected. Litherland and Ferguson (Li 61) have developed a method for determining the population parameters, $P(m)$, for the magnetic substates which have non-zero population parameters because of the solid angle of

the counter. This correction can only be made when details of the formation and decay of the intermediate state are available. If these details of the intermediate state are not known, then the contribution to the correlation from magnetic substates higher than $m = \pm 1/2$ remains uncertain. This is a problem that must be faced in the analysis of the results described in this thesis.

1.2 Theory of Triple Angular Correlations

Many authors have written articles on the theory of triple angular correlations. They have developed equations which contain the angular momentum information of the nuclear states. In particular, it has been shown independently by Fano (Fa 53) and by Coester and Jauch (Co 53) that there is great advantage in representing the intensity distribution, $W(\theta)$, of one member of a double cascade with respect to the other by the expression

$$W(\theta) = \text{Trace } \rho \epsilon$$

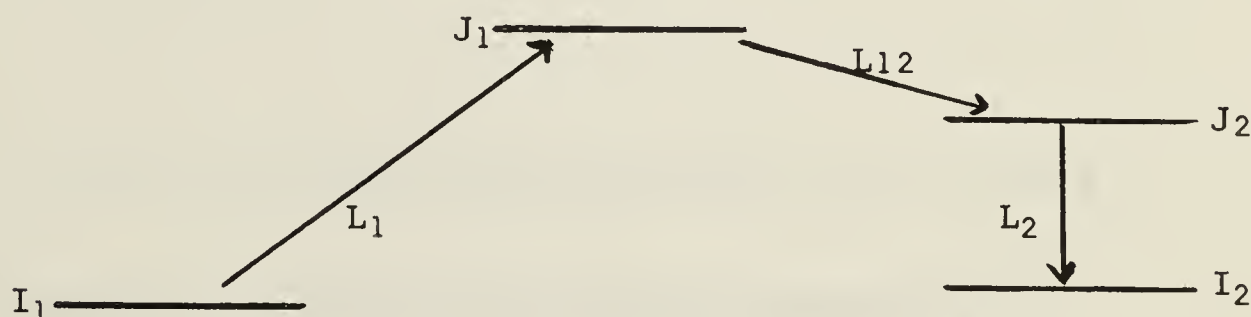
The letter ρ represents a matrix called the density matrix. According to the probability theory of quantum mechanics it contains all that can be known about the state. ϵ is the efficiency matrix which is characteristic of the detection of the outgoing radiation. Both of these matrices can be represented in terms of irreducible tensors. Devons and Goldfarb (De 57, Go 59) derive the forms of these two matrix elements and show that a triple correlation of radiations is represented by the sum of products of these density and efficiency tensors. The

expression for a triple angular correlation is then given by the general equation

$$W(\theta_1\theta_{12}\theta_2\phi_1\phi_{12}\phi_2) = \sum A_{K_1K_2K_{12}} \Lambda_{K_1K_2K_{12}}(\theta_1\theta_{12}\theta_2\phi_1\phi_{12}\phi_2).$$

The summation in this equation is over $L_1L_1'L_2L_2'L_{12}L_{12}'K_1K_2K_{12}J_1J_2$.

Assume that the order of the radiation in time is L_1, L_{12} , and L_2 between the states I_1 and J_1 , J_1 and J_2 , and J_2 and I_2 , and their polar directions are $(\theta_1\phi_1)$, $(\theta_{12}\phi_{12})$, and $(\theta_2\phi_2)$ with respect to some fixed axis. An example of this is the $O^{18}(\alpha n\gamma)Ne^{21}$ reaction where the angular momentum of the alpha particle is L_1 , the neutron L_{12} and the gamma ray L_2 .



The term $\Lambda_{K_1K_2K_{12}}$ contains the angular dependence while the term $A_{K_1K_2K_{12}}$ contains only factors dependent on angular momenta.

$$A_{K_1 K_2 K_{12}} = \sum_{\mu_1 \mu_2} (K_1 K_2 \mu_1 \mu_2 | K_{12} \mu_1 + \mu_2) \left[\frac{(4\pi)^3}{(2K_1+1)(2K_2+1)(2K_{12}+1)} \right]^{1/2} \times$$

$$Y_{K_1}^{\mu_1}(\theta_1 \phi_1) Y_{K_2}^{\mu_2}(\theta_2 \phi_2) Y_{K_{12}}^{\mu_1 + \mu_2}(\theta_{12} \phi_{12})$$

$$A_{K_1 K_2 K_{12}} = (-1)^\lambda g C_{K_1 0}(L_1 L_1')^* C_{K_2 0}(L_2 L_2')^* C_{K_{12} 0}(L_{12} L_{12}') W(L_1 J_1 L_1' J_1' I_1 K_1)$$

$$W(L_2 J_2 L_2' J_2' I_2 K_2) X \begin{pmatrix} J_1 J_2 L_{12} \\ J_1' J_2' L_{12}' \\ K_1 K_2 K_{12} \end{pmatrix}$$

$$\lambda = I_1 + I_2 + L_1 + L_2 + L_{12} + L_{12}' - J_1 - J_2 + K_{12}$$

$$g = \left[(2J_1+1)(2J_1'+1)(2J_2+1)(2J_2'+1)(2K_1+1)(2K_2+1) \right]^{1/2}$$

$$C_{K0}(LL') = \sum_m (-1)^{L-m} \alpha(Lm)^* \alpha(L'm)(LL' - mm|K0)$$

$\alpha(Lm)$ = wave function giving polarization state of particle of angular momentum L .

The coefficient $W(LJLJ, IK)$ is a Racah coefficient defined and tabulated by Biedenharn (Bi 53) and the X coefficient is defined and tabulated by Sharp (Sh 54). The summation in the correlation equation is to be extended over all values of $K_1 K_2$ and K_{12} consistent with the triangular conditions for the W and X coefficients. For states of sharp spin and parity, the conservation of parity requires that $K_1 + K_2 - K_{12}$ be even.

Calculation of the large number of Λ 's and A's is tedious. In practice it is convenient to take the Z axis as the direction of the bombarding particle. This eliminates one of the summations in Λ . For $\theta_1 = 0$ and $\phi_1 = 0$,

$$\begin{array}{lll} Y_{K_1}^{\mu_1} (0 \ 0) & \longrightarrow & \sqrt{\frac{2K_1+1}{4\pi}} \quad \text{for } \mu_1 = 0 \\ & \longrightarrow & 0 \quad \text{for } \mu_1 \neq 0 \end{array}$$

Thus

$$\Lambda_{K_1 K_2 K_{12}} = \sum_{\mu_2} (K_1 K_2 0 \mu_2 | K_{12} \mu_2) \left[\frac{(4\pi)^2}{(2K_2+1)(2K_{12}+1)} \right]^{1/2} Y_{K_2}^{\mu_2}(\theta_2 \phi_2) Y_{K_{12}}^{\mu_{12}}(\theta_{12} \phi_{12})$$

Using the relationship

$$Y_{\ell}^m(\theta \phi) = \sqrt{\frac{(2\ell+1)(\ell-m)!}{4\pi(\ell+m)!}} (-1)^m e^{im\phi} P_{\ell}^m(\cos \phi)$$

Λ becomes

$$\Lambda_{K_1 K_2 K_{12}} = \sum (K_1 K_2 0 \mu_2 | K_{12} \mu_2) \left[\frac{(K_2 - \mu_2)! (K_{12} - \mu_2)!}{(K_2 + \mu_2)! (K_{12} + \mu_2)!} \right]^{1/2} \times$$

$$e^{i\mu_2(\phi_2 - \phi_{12})} P_{K_2}^{\mu_2}(\theta_2) P_{K_{12}}^{\mu_2}(\theta_{12}).$$

Litherland and Ferguson (Li 61) express the angular dependent part in terms of $X_{K_2 K_{12}}^{\mu_2}$:

$$X_{K_2 K_{12}}^{\mu_2}(\theta_{12} \theta_2 \phi) = \left[\frac{(2K_2 + 1)(K_2 - \mu_2)!(2K_{12} + 1)(K_{12} - \mu_2)!}{(K_2 + \mu_2)!(K_{12} + \mu_2)!} \right]^{1/2} \times$$

$$P_{K_2}^{\mu_2}(\theta_2) P_{K_{12}}^{\mu_2}(\theta_{12}) \cos 2\phi.$$

Then

$$\Lambda_{K_1 K_2 K_{12}} = \sum_{\mu_2} (K_1 K_2 0 \mu_2 | K_{12} \mu_2) [2K_2 + 1]^{-1/2} [2K_{12} + 1]^{-1/2} X_{K_2 K_{12}}^{\mu_2}$$

where $\phi = \phi_{12} + \phi_2$.

The general equation for triple correlations in nuclear reaction work can now be expressed as

$$W(\theta_2 \theta_{12} \phi) = \sum_{K_2 K_{12} \mu_2} a_{K_2 K_{12}}^{\mu_2} X_{K_2 K_{12}}^{\mu_2}(\theta_1 \theta_{12} \phi) \quad (2.1)$$

where

$$a_{K_2 K_{12}}^{\mu_2} = (K_1 K_2 0 \mu_2 | K_{12} \mu_2) [2K_2 + 1]^{-1/2} [2K_{12} + 1]^{-1/2} \Lambda_{K_1 K_2 K_{12}}$$

K_2 and K_{12} are determined again by the multipolarities of the radiations and the triangle conditions of the coefficients. If the states have sharp spin and parity, the conservation of parity requires that K_2 and K_{12} remain even. If the highest radiation is restricted to quadrupole, there are 19 terms in this series. Thus the number of measurable parameters generally exceeds the number of unknowns. This is very complicated to analyse and to simplify the analysis one of the three remaining angles is fixed while the others are left as variables. This reduces $X_{K_2 K_{12}}^{\mu_2}$ to an associated Legendre polynomial. If one of these angles is fixed at 90° , only even associated Legendre polynomials are involved and each of these can be reduced to a sum of even ordinary Legendre polynomials. If one of the angles is fixed at 0° or 180° , $X_{K_2 K_{12}}^{\mu_2}$ reduces to an even Legendre polynomial. These special combinations of angles are called geometries and Litherland and Ferguson (Li 61) define a number of them as

Geometry	θ_{12}	θ_2	ϕ
I	variable	90°	180°
II	90°	variable	180°
III	variable	0°	0°
IV	0°	variable	0°
V	90°	90°	variable
VI	90°	variable	90°
VII	variable	90°	90°

Table 1.1

Six geometries yield $W(\theta)$ in terms of $P_K(\cos \theta)$ while geometry V yields $W(\theta)$ in terms of $\cos \phi$. For all other geometries the correlation is in terms of associated Legendre polynomials. For instance, $\theta_{12} = 45^\circ$ results in $P_2^1(\cos \theta)$, $P_4^1(\cos \theta)$, $P_4^3(\cos \theta)$, $P_0(\cos \theta)$, $P_2(\cos \theta)$, and $P_4(\cos \theta)$ terms.

Using these special geometries then, the correlation is reduced to a form in which the angular dependent factor of each term is an ordinary Legendre polynomial or a cosine function. This reduces the complexity of the analysis, but the problem of calculating $a_{K_2 K_{12}}^{\mu_2}$ still remains. To ease the calculation of these coefficients, Sharp, Kennedy, Hoyle, Ferguson, Rutledge, and Sears (Fe 57, Sh 54) have reduced this product of coefficients to simpler forms and tabulated the condensed coefficients.

The study of Ne^{21} using the $\text{O}^{18}(\alpha\gamma)\text{Ne}^{21}$ reaction uses geometry IV. The neutrons are detected at zero degrees while the intensity distribution of the gamma ray is observed. Sharp and co-workers give the following equation for this case.

$$W_{LL'}(\theta) = \sum_K (-1)^f Z(\ell_1 J_1 \ell_1 J_1, 0K) W(J_1 J J_1 J, 1/2 K) Z_1(L J L' J I K) Q_K P_K(\cos \theta) \quad (2.2)$$

$$f = I - 1/2 + L + L'$$

This equation describes the correlation of a gamma ray of quantum L , emitted from the magnetic substates, $m = \pm 1/2$ of a level of spin J to a level of spin I . The disadvantage of this method is that assumptions

must be made concerning the formation of the state J. For example, in the present experiment the O^{18} nucleus absorbs an incident alpha particle of orbital angular momentum l_1 forming the state of spin J_1 in Ne^{22} which decays by emitting an s wave neutron forming the state J. J_1 and l_1 are not known in general, and because of the high level density of Ne^{22*} , may not be unique. The coefficients $Z(l_1 J_1 l_1 J_1, 0K)$, $W(J_1 J J_1 J, 1/2 K)$, and $Z_1(L J L' J, IK)$ are defined and tabulated by Sharp (Sh 54). Q_K is a correction term for the finite solid angle of the gamma ray counter which is defined and tabulated in Section 2.2 for the counters used in this experiment.

The full expression for the angular correlation must include a sum over the different multipole radiations that may be present. For a dipole-quadrupole case, the full expression is

$$W(\theta) = W_{11}(\theta) + 2\delta W_{12}(\theta) + \delta^2 W_{22}(\theta)$$

The dipole-quadrupole mixing term is represented by δ . In general

$$\delta = \frac{\langle b || L + 1 || a \rangle}{\langle b || L || a \rangle}$$

where $\langle b || L || a \rangle$ is a reduced matrix element proportional to the L multipole amplitude.

This expression becomes quite difficult to use when calculations of contributions from magnetic substates other than $m = \pm 1/2$ are to be made. It involves extensive summations over vector coupling coefficients

and requires knowledge of the formation and decay of the intermediate state.

Litherland and Ferguson (Li 61) introduce a more convenient theoretical expression for the observed gamma ray correlations. This expression is in terms of an ordinary Legendre polynomial and the angular momentum dependent factor, $a_{K_2 K_1 2}^{\mu_2}$, is reduced to a function of the population parameter, $P(m)$ and a condensed set of coefficients. The population parameter is the relative probability that the substate, m , is populated. Their form for W is

$$W_{LL'}(\theta) = \sum_{K m} (-1)^f P(m) (JJm-m|K0) Z_1(LJL'J, IK) Q_K P_K(\cos \theta) \quad (2.3)$$

where $f = I + m + L + L' + K/2$.

In this equation, $P(m)$ is the population parameter for substate m of the nuclear state of spin J , which decays to another state of spin I by emitting a gamma ray quantum of total angular momentum L . The coefficient $(JJm-m|K0)$ is a Clebsh-Gordan coefficient defined and tabulated by Sears and Radtke (Se 54) and Rotenberg, Bivins, Metropolis, and Wooten (Ro 59). The coefficient $Z_1(LJL'J, IK)$ has been defined and tabulated by Sharp, Kennedy, Sears and Hoyle (Sh 54).

This expression has the advantage that it does not need information concerning the formation of the state J . It provides the most general expression for both the correlations employing restrictive geometries and distributions where the intermediate radiation is unobserved, so

that the only restriction on magnetic substates is from the formation and decay process of the intermediate state. In the case employing restrictive geometries, $P(1/2)$ and possibly $P(3/2)$ may be non-zero because of the finite detector solid angle. This introduces a second parameter $P(3/2)/P(1/2)$, as an unknown. This normalized population parameter will be designated as $P'(m)$ throughout the text of this thesis.

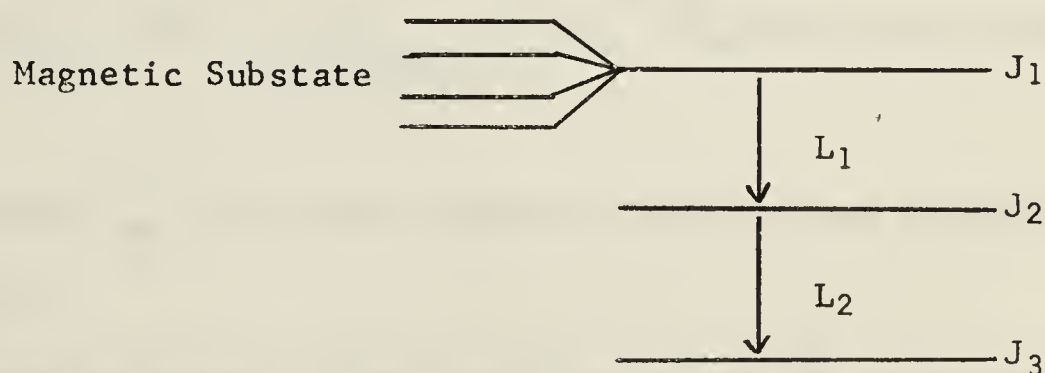
This equation has a form which allows calculation of the predicted correlation for the case where the intermediate radiation is unobserved. The only restrictions on the magnetic substates are imposed by the coupling of spins and orbital angular momentum of the intermediate level and particles feeding the excited state. If the intermediate particle is s wave and the input channel spin is zero, then only the magnetic substates, $m = \pm 1/2$, are populated. This situation is unique and in general the values of the spin and orbital angular momentum of the intermediate level and particle are not predictable so that the population parameters have to be treated as unknowns.

Appendix A is a list of the angular correlation equations derived from equation 2.3 for the spin combinations needed in the analysis of the data of this experiment. All of the population parameters are included for each equation.

In a cascade gamma-ray decay the intensities of the different components of the cascade in coincidence can be measured as a function of the various angles describing the processes. Such experiments are

much more difficult than double correlation experiments, but give a great deal more information. Litherland, Ferguson, Batchelor and Gove (Li 61, Ba 60) have demonstrated the feasibility of these correlations in nuclear reactions and have shown that the alignment achieved by a nucleus capturing an unpolarized particle incident along the z-axis followed by one or more unobserved radiations in cascade is indistinguishable from the alignment achieved in some other fashion. They have shown how to predict the form of the correlations using the existing tables of Ferguson and Rutledge (Fe 57). Calculations performed by their method are inconvenient and tedious. To eliminate this problem, Smith (Sm 64, Sm 64a) has completed a set of tables which allow the predicted gamma-gamma correlations to be calculated more conveniently in the population parameter form.

The analysis requires that the state J_1 is formed in some way and some degree of alignment has occurred in the process.



For this example, the unknowns for a set of spin values include the electromagnetic mixing ratios of the radiations L_1 and L_2 , and the

normalized population parameters which number one less than the total number of population parameters. The correlation is a function of three angles, θ_1 and θ_2 , the angles between the beam axis and the gamma ray counters 1 and 2 respectively, and ϕ the angle between the two planes passing through the counters and the beam axis. The correlation is expressed as

$$W(\theta_1\theta_2\phi) = \sum_{KMN} a_{KM}^N x_{KM}^N(\theta_1\theta_2)$$

This is equation 2.1 with a slight change in notation for convenience.

$$K = K_2 \quad M = K_{12} \quad N = \mu_2 \quad \theta_1 = \theta_2 \quad \theta_2 = \theta_{12}$$

Smith condenses the original coefficients of a_{KM}^N into a form that is convenient to calculate.

The coefficient a_{KM}^N is

$$a_{KM}^N = \sum_m P(m) \sum_{L_1 L_1' L_2 L_2'} \delta_1^{P_1} \delta_2^{P_2} C_{KM}^N(J_1 J_2 J_3 L_1 L_1' L_2 L_2' m)$$

The coefficient $C_{KM}^N(J_1 J_2 J_3 L_1 L_1' L_2 L_2' m)$ is defined and tabulated in Smith (Sm 64).

The possible mixing of multipole radiations is represented by δ_1 and δ_2 for the radiations L_1 and L_2 respectively. $P_i = 0$ for $(L_i L_i') = (11)$, $P_i = 1$ for $(L_i L_i') = (12)$, and $P_i = 2$ for $(L_i L_i') = (22)$ for dipole quadrupole mixing.

If two of the three angles are fixed at values corresponding to the geometries of this section, the predicted correlation may be expressed in terms of an ordinary Legendre polynomial.

$$X_{KM}^N(\theta_1\theta_2\phi) = \sum_r \alpha_{rKM}^N P_r(\cos \theta) \quad \text{for a given geometry}$$

so that

$$W(\theta) = \sum_{rKM} \alpha_{rKM}^N Q_K Q_M a_{KM}^N P_r(\cos \theta)$$

The coefficient α_{rKM}^N is geometry dependent and is tabulated by Ferguson and Rutledge (Fe 57).

In the calculations, K and M can have values of 0, 2, and 4 for dipole and quadrupole radiation while the index N is limited to zero and positive integral values such that the absolute value of N does not exceed either K or M.

The expression may be put into a more familiar form.

$$W(\theta) = \sum_r A_r^{(i)} P_r(\cos \theta)$$

where

$$A_r^i = \sum_m P(m) \sum_{L_1 L_1' L_2 L_2'} \delta_1^{P_1} \delta_2^{P_2} \sum_{KMN} \alpha_{rKM}^N Q_K Q_M C_{KM}^N (J_1 J_2 J_3 L_1 L_1' L_2 L_2' m) \quad (2.4)$$

$$r = 0, 1, 2 \dots$$

The letter i represents the coefficients for a particular geometry.

The coefficients $A_r^{(i)}$ are the unnormalized coefficients and may be normalized so as to have

$$W(\theta) = 1 + \sum_r B_r^{(i)} P_r(\cos \theta) \quad r > 0$$

where

$$B_r^{(i)} = \frac{A_r^{(i)}}{A_0^{(i)}}$$

The Nuclear Research Center of the University of Alberta does not have a computer program at present to handle the gamma-gamma correlations in a convenient manner, so only the correlation equation for one spin combination has been calculated, the $7/2$ to $5/2$ to $3/2$. This spin combination is used in the gamma-gamma correlation analysis of this experiment and the predicted correlation is given in Appendix B.

1.3 Review of Previous Work on Ne^{21}

The nucleus Ne^{21} consists of 10 protons and 11 neutrons. An energy level diagram is shown in Figure 1.1. In shell model language one considers the last two protons and last three neutrons as being in the $1d_{5/2}$ shell. Thus the simplest version of the shell model predicts a spin of $5/2^+$ for the ground state. Along with this one finds that the magnetic dipole moment is -1.91 nm and the electric quadrupole moment is zero. Grosos, Buck, Lichten and Rabbi (Gr 58) have measured the spin and parity of the ground state to be $3/2^+$ and

the electric quadrupole moment at $+0.093 \times 10^{-24} \text{ cm}^2$. La Tourette, Quinn, and Ramsey (La 57) have measured the magnetic moment to be -0.662 nm . Obviously there is very poor agreement here and modifications to this model must be made or a new model devised. Flowers (Fl 52) has calculated a value of -1.27 nm for the ground state magnetic dipole moment by considering all particles outside the core of a completed shell on an equal footing whether they are paired or not. He has obtained, in general, better agreement with experimental moments than that obtained with the simpler model.

Rakavy (Ra 57) performed some calculations using a strong coupling collective rotational model for nuclei in the s-d shells. He finds that the deformation increases very rapidly between $A = 16$ and $A = 25$ suggesting that rotational spectra should be found in this region. He concludes that the ground state of Ne^{21} must be $3/2^+$ and it is the $3/2$ band head on which the second and third excited states are built giving $5/2^+$ and $7/2^+$ respectively.

Using the same type of collective model, Paul and Montague (Pa 58) made calculations for Na^{23} . They arranged the three rotational bands $K = 1/2$, $3/2$, and $5/2$ of the $d_{5/2}$ level to get the lowest $3/2^+$, $5/2^+$, and $1/2^+$ levels by means of the rotational particle coupling interaction term.

Freeman (Fr 60) applied this model to Ne^{21} . By fixing the coupling interaction term for the same three rotational bands she obtains the level sequence $3/2^+$, $5/2^+$, $7/2^+$, $1/2^+$, $5/2^+$, $9/2^+$, $3/2^+$, and $5/2^+$, but the energy agreement is not very good for most of the levels.

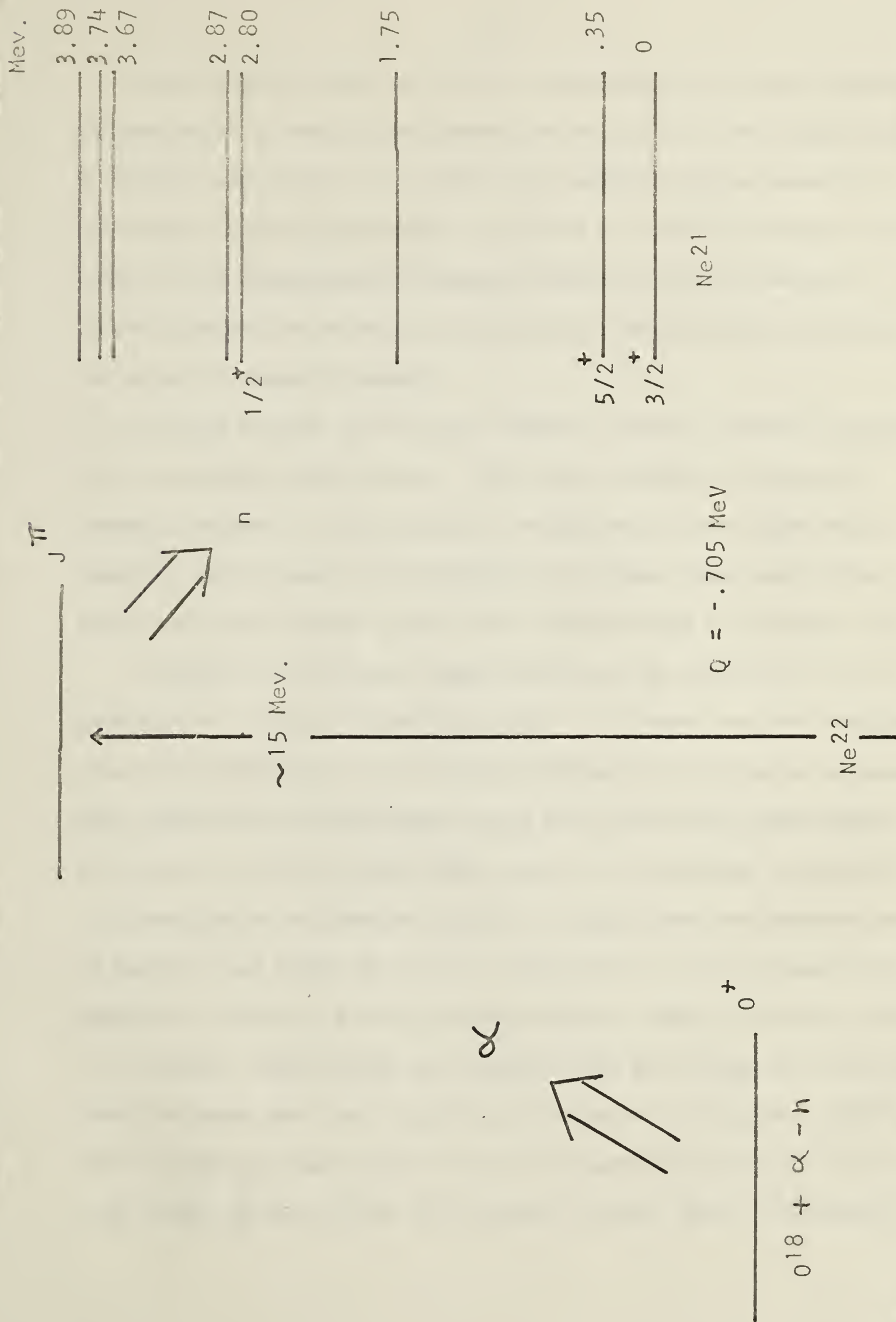


FIG.1-1 A SCHEMATIC OF THE REACTION $^{18}\text{O}(\alpha, n)^{21}\text{Ne}$.

More recently Bhatt (Bh 62) has used the extreme single-particle Nilsson model to predict the properties of nuclei in the 1d-2s shell. A positive deformation of $\eta = +3$ gives a magnetic dipole moment of -0.66 nm. Larger deformations are needed for better agreement in the value of the reduced matrix element, $B(E2 \ 3/2 \rightarrow 5/2)$, but using a larger deformation parameter destroys the relatively good agreement in energy and magnetic moment.

Chi and Davison (Ch 63) use a model in which a nucleon is coupled to an asymmetric, rotating core. They have obtained a reasonable energy spectrum and find a value of -0.566 nm for the ground state magnetic dipole moment. The agreement in ground state quadrupole moment and the lifetime of the first excited state is extremely poor.

Dreizler (Dr 63) uses a model employing the coupling of a 2s-1d particle to a rotational Ne^{20} core with a different coupling Hamiltonian than Chi and Davison's. His energy spectrum is in no better agreement with experiment than the models using the Nilsson type Hamiltonian. His calculated E2-M1 mixing ratio based on the lifetime measurement of Khabakhpashev and Tsenter (Kh 59) is higher than the measured value of Deuchars and Dandy (De 61) by a factor of ten. The ground state quadrupole moment is higher than the measured value by the same factor.

Burrows, Green, Hinds and Middleton (Bu 56), using the $\text{Ne}^{20}(\text{d}, \text{p})\text{Ne}^{21}$ reaction found from the stripping distribution of the protons $3/2^+$ or $5/2^+$ for the spin and parity of the first excited state, $1/2^+$ for the 2.80 MeV level and $3/2^+$ or $5/2^+$ for the 4.58 MeV level. Much more

recently Howard, Bromley and Warburton (Ho 63) have used this reaction for an investigation of the gamma rays and found $5/2^+$, $7/2^+$, $1/2^+$, and $3/2^-$, as the most probable spins of the 0.35 MeV, 1.75 MeV, 2.80 MeV, and 4.73 MeV levels respectively.

Deuchars and Dandy (De 61) investigated the 0.35 MeV level using the $O^{18}(\alpha\gamma)Ne^{21}$ reaction at a bombarding energy of 2.73 MeV. They found the first excited state to be most probably $5/2$ with an E2-M1 mixing ratio in the range $+0.004 < \delta < +0.03$. They were unable to excite the 1.75 MeV level.

This was the available knowledge of the Ne^{21} spectrum at the start of this experiment. The following work has been reported since the experiment was begun.

A group at Harwell, Bent, Evans, Morrison, and Van Heerden (Be 63), have measured lifetimes in Ne^{21} by the Doppler shift attenuation method using 24 MeV O^{16} ions in the $Be^9(O^{16},\alpha\gamma)Ne^{21}$ reaction. They found the mean lives of the 1.75 MeV, 2.80 MeV, and 2.87 MeV levels to be, in units of 10^{-13} seconds, $1.1_{-0.7}^{+1}$, $1.1_{-0.9}^{+1.5}$, and $1.4_{-0.85}^{+1.4}$ respectively. They found that the 1.75 MeV level decays approximately 10% of the time to the ground state, the 2.80 MeV level decays 60% to the ground state and 40% to the first excited state, and the 2.87 MeV level decays 30% to the first and 70% to the second excited state. From this information they deduced a spin of $9/2$ for the 2.87 MeV level. Using Freeman's (Fr 60) band heads, $h^2/2I = .25$ MeV, and $\eta = 9$ they calculated the ground state magnetic moment to be -0.77 nm which

is in reasonable agreement with experiment. They also calculated transition probabilities which were in agreement with experiment.

A group at Freiburg, Germany, Pelte, Povh, and Scholz (Pe 64), have completed an experiment using the reaction $F^{19}(He^3, p\gamma)Ne^{21}$. They found the 1.75 MeV level to have spin 7/2 and an E2-M1 mixing ratio of $\delta = +0.11 \pm 0.04$ for the transition to the 5/2 state at 0.35 MeV. A value of 6% for the transition rate to the ground state from the 1.75 MeV level and a branching ratio of 50:50 to the ground and first excited state from the 2.80 MeV level were found. The 3.67 MeV level was found to have a 3/2 or 1/2 spin value.

Howard, Bromley, and Warburton (Ho 65)* have measured some branching and mixing ratios for gamma rays from the $Ne^{20}(d, p\gamma)Ne^{21}$ reaction as well as the spin values of the states involved. They found the E2-M1 mixing ratio of the 0.35 MeV level to be $+0.005 \pm .025$. They found that the 1.75 MeV level decays 7% of the time to the ground state and the 2.80 MeV level decays 10% to the 0.35 MeV level and 90% to the ground state. A mean lifetime measurement yielded $\tau < 3 \times 10^{-10}$ seconds for the 0.35 MeV level.

All of the lifetimes of the levels studied in this work, have lifetimes that were measured to be shorter than 10^{-10} seconds. (Ho 65, Kh 59, Be 63). This is short enough to be sure that external perturbing forces will not disturb the correlation or distribution of the intensities.

*

I wish to express my gratitude to Dr. D. A. Bromley for communicating this information prior to publication.

CHAPTER II. EXPERIMENTAL ASPECTS

2.1 Experimental Equipment

(a) Accelerator and Correlation Table

The experiment was performed at the Nuclear Research Center of the University of Alberta. The alpha particles were obtained from a 5.50 MeV Model CN Van de Graaff accelerator.* Figure 2-1 is an illustration of the beam path.

Stabilization of the beam energy is accomplished by passing the beam through a 90° double focusing sector magnet of radius 28.5 in. and a pair of slits four feet from the analyzing magnet. The current balance on these slits is maintained by a feedback circuit controlling the impedance of the corona loading of the accelerator terminal. This system limits the energy spread of the beam at the target to less than 5 keV. As illustrated in Figure 2-1, the beam then passes through a cold trap, switching magnet and quadrupole lens. The straight through port on the switching system was used, so that the switching magnet was used only for slight steering into the quadrupole lens. Beyond the quadrupole lens is a set of horizontal and vertical slits for defining the beam. A carbon trap and cylindrical lead slug, 3 in. long with an 1/8 in. hole drilled along the axis and with tantalum on

*High Voltage Engineering, Burlington, Massachusetts, U.S.A.

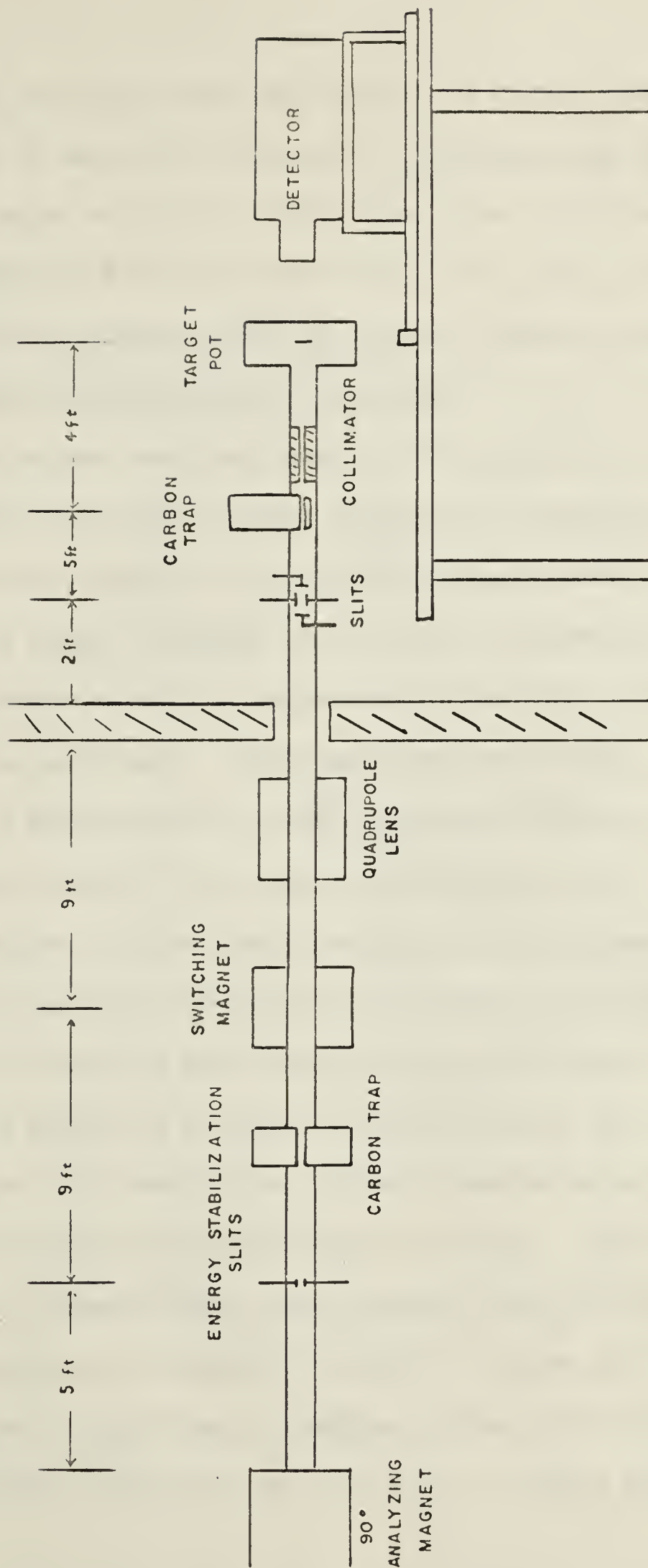


FIG. 2-1 AN ILLUSTRATION OF THE BEAM PATH.

its face, are positioned just before the target chamber. The lead cylinder is used as a collimator to keep the beam as close as possible to the center axis of the drift tube. The target chamber is an aluminum cylinder 2.5 in. in diameter and 12 in. long. This chamber has an air-cooled target holder so designed that the target position can be changed without breaking the vacuum.

The targets used were made of O^{18} , isotopically enriched, deposited on a 0.005 in. thick tantalum backing and produced by the Isotope Group, Atomic Energy Research Establishment, Harwell, England. The effective target thickness at 2.50 MeV was approximately 20 keV for α particles. Two different targets of approximately the same thickness were used during the experiment. With compressed air cooling, the targets showed no deterioration if the current was kept at a value which produced 6 watts or less dissipation on the target.

The distributions and correlations were measured on a horizontal table, the center of which is fixed directly beneath the target chamber. Figures 2-2 and 2-3 are illustrations of the table design. The table itself is made of a circular piece of masonite diestock 24 inches in radius and 1/2 inches thick. This is mounted on a supporting framework of welded angle iron mounted on wheels. The bottom of this support is weighted with lead to make it as rigid as possible. The whole table can be leveled by stand-off screws at the base which takes the weight off the wheels. Mounted on the table are two movable arms pivoted about the center of the table. On these arms can be mounted

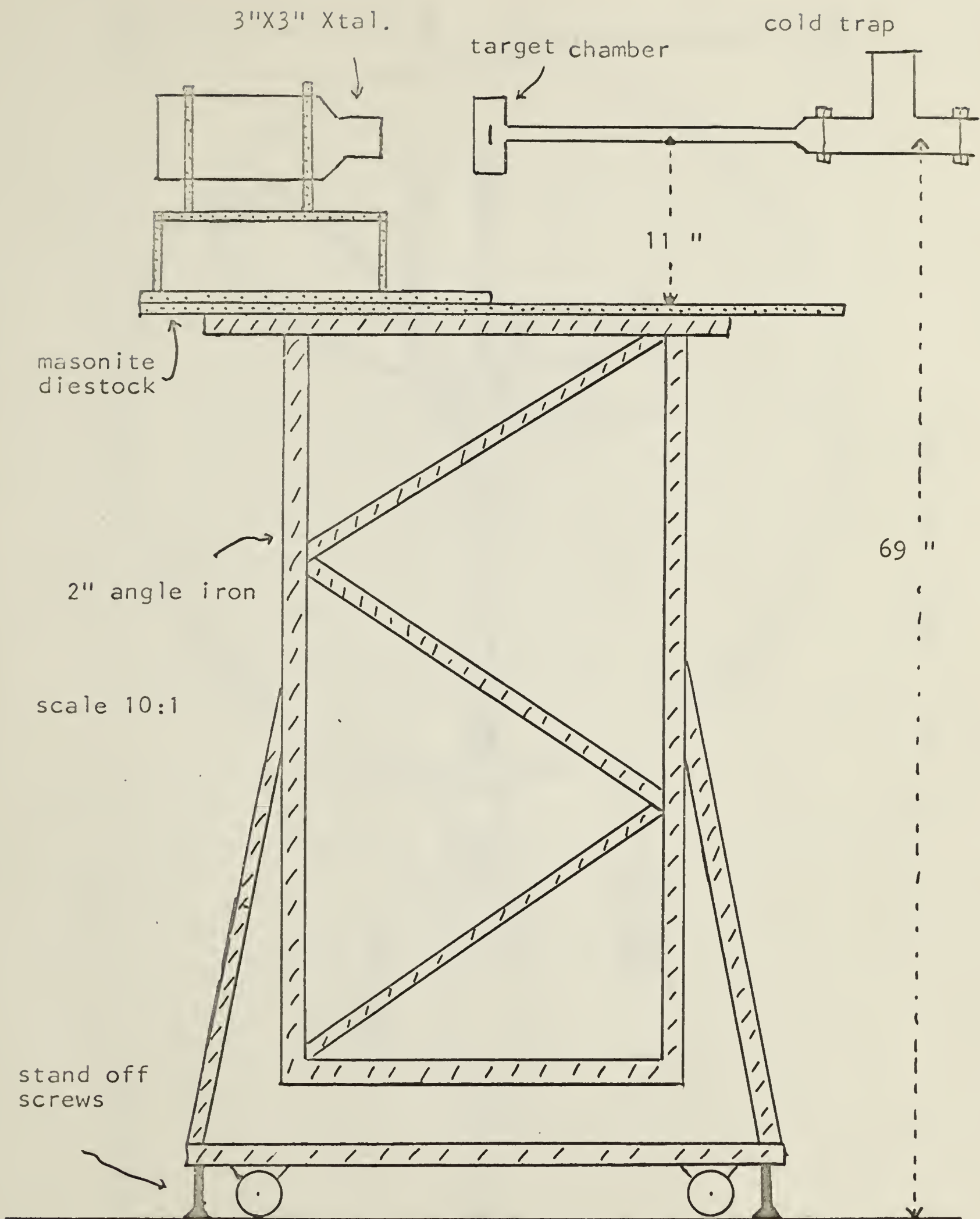


FIG. 2-2 SIDE VIEW OF CORRELATION TABLE.

scale 10:1

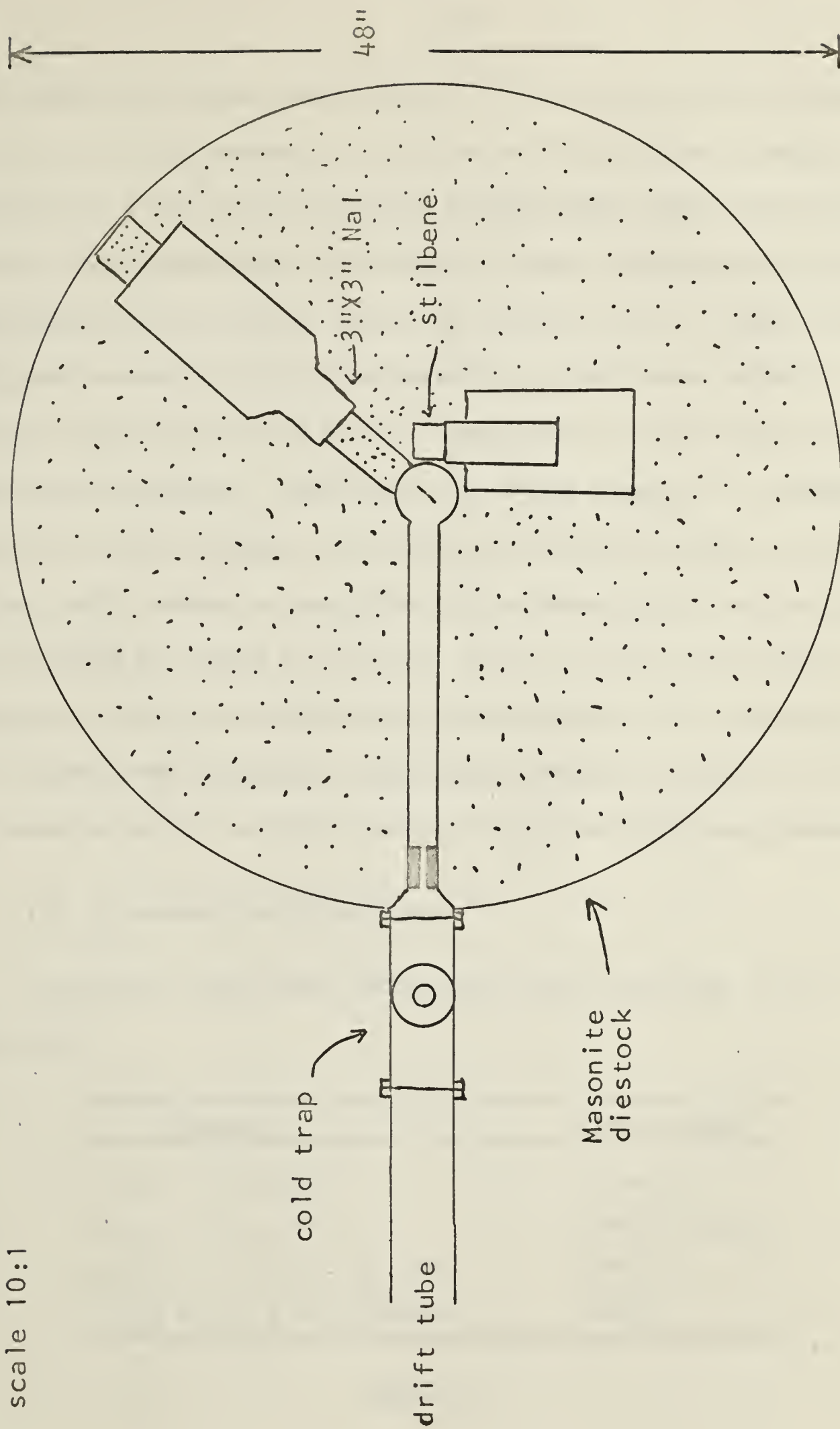


FIG.2-3 TOP VIEW OF CORRELATION TABLE.

four detection systems consisting of a 3 in. x 3 in. NaI crystal, a 4 in. x 4 in. NaI crystal, a 1-3/4 in. x 1-1/2 in. NaI crystal, and a 1-1/2 in. x 1 in. stilbene crystal together with their photo-tubes, headers and preamplifiers. The axes of these crystals are 11 in. above the table and 69 in. above the concrete floor. These distances are great enough to reduce the intensity of scattered radiation to a level acceptable in the present experiment, so shielding is not used on the detectors. The table and target chamber are aligned optically with a transit and checked periodically during an experiment. Using a point source of radiation in the center of the target chamber, the isotropy was found to be better than 3 per cent. The table is designed so that the movable arms may be locked at 5° intervals. A 15° interval was chosen as a compromise between reliability of the correlation curves and time consumed per correlation measurement.

(b) Detectors and Electronics

The crystal photo-tube combinations used are given in the following table.

Crystal	Photo-tube
4 in. x 4 in. NaI	7046 RCA
3 in. x 3 in. NaI	54AVP Philips
1-3/2 in. x 1-1/2 in. NaI	6342 RCA
1-1/2 in. x 1 in. Stilbene	56AVP

Table 2.1

A schematic diagram of the electronic equipment is given in Figure 2-4. Each counter used was mounted on the table arm with a header, linear preamplifier and a limiter. This constituted the start of a fast slow coincidence system. The linear preamplifier develops the pulse used for energy discrimination and is fed by a pulse from a dynode as is illustrated in Figure 2-5. The pulse from the preamplifier traverses approximately 80 feet of cable to the data collection area where it is amplified and analysed. The limiter is also fed by a pulse from a dynode and is illustrated in Figure 2-5. The limited pulse appears in the data collection area as a pulse one volt high and 60 nanosecond clipping cable in the limiter. Any length of clipping cable from about 80 nanoseconds down can be used and this value determines the maximum value of the resolving time.

For coincidence work, the limited pulses from each detector are amplified by wide band distributed amplifiers* and passed into a time to amplitude converter (Ne 60) whose output is fed into single channel analyser (Go 60a). By narrowing the window on the pulse height analyser, a resolving time smaller than that of the shorting stub can be obtained. During the experiment the window was left wide open so that the resolving time was determined by the width of the limiter pulse giving $2T \approx 120$ nsec. The single channel pulse height analyser generates a gating pulse which is 1 microsecond wide and

*Model 460 AR, Hewlett-Packard Corporation, Palo Alto, California

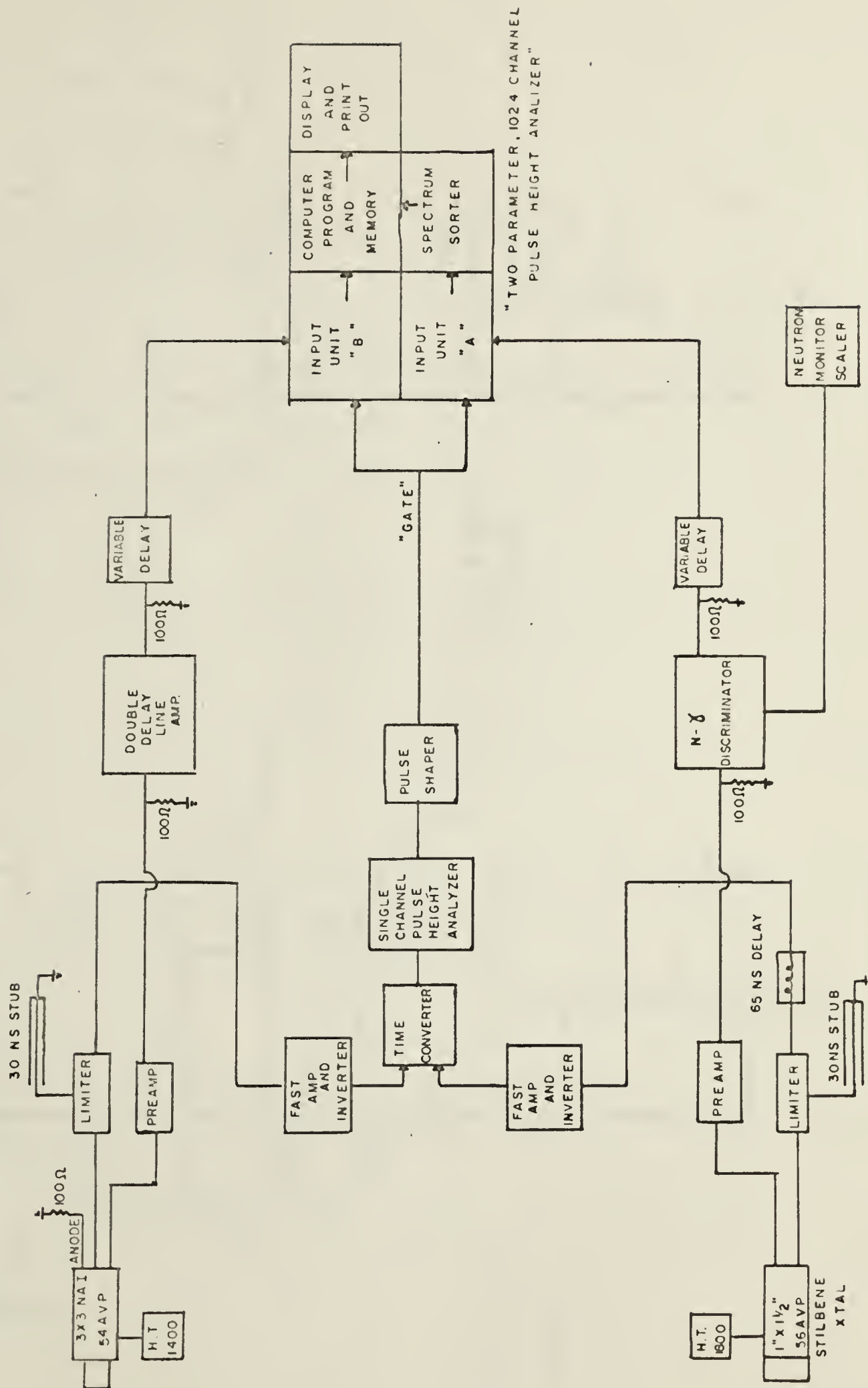


FIG 2-4 AN ILLUSTRATION OF THE ELECTRONICS

1 volt high. This passes through a pulse shaping system which produces a 10 volt square pulse whose width can be varied between 1.0 microseconds and 5.0 microseconds in 0.5 microsecond steps. This pulse is used as a gating pulse for a 1024 channel, two parameter, pulse height analyser*. Any time differences in the fast circuits are cancelled with a delay line inserted in series with the 80 feet of transit cable from the limiters. This timing is checked occasionally using a Na^{22} annihilation radiation for producing coincidence and an oscilloscope.

The slow pulses from the linear preamplifiers (Go 60) traverse delays** which can be varied continuously from 0 to 4.5 microseconds with no appreciable distortion in the pulse. These delays cancel the time difference between the fast and slow channels of the system. Pulses from the NaI crystals are amplified by double delay line amplifiers and fed into the "B" input of the two parameter, 1024 channel pulse height analyser.

Pulses from the stilbene neutron counter are fed into a neutron-gamma-ray discriminator designed by Alexander and Goulding (A1 61). Their method measures the slow to total charge ratio at the photomultiplier dynode. Two bands of pulses appear at the output of the

* Technical Measurements Corporation, 441 Washington Avenue, North Haven, Connecticut, U.S.A.

** Ad-Yu Electronics Inc., Passaic, New Jersey, U.S.A.

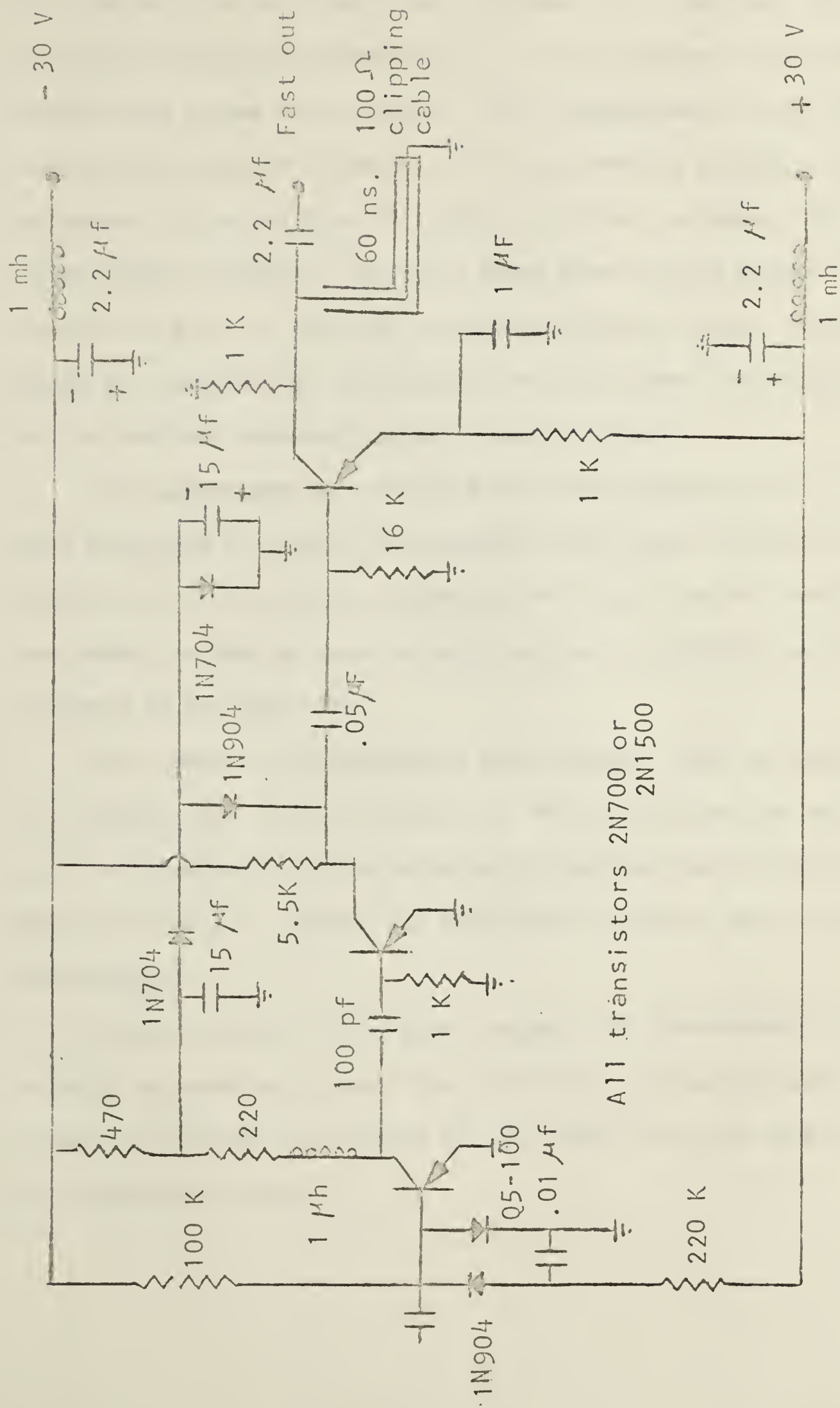


FIG. 2-6 LIMITER CIRCUIT (BROWN-TOMLINSON, CHALK RIVER).

discriminator as is illustrated in Figure 2-7. One group of pulses represents the pulses identified as arising from gamma rays and the other those pulses from neutrons. The discriminator is set and checked periodically to ensure that it is working properly. This group of pulses is fed into the "A" input of the two parameter 1024 channel pulse height analyser. The patch board gate setting system is set so that it gates on the peak representing the neutrons. The neutron-gamma ray correlations are measured with the gamma ray spectrum selected by the neutrons detected in the stilbene crystal.

When gamma-gamma correlations are being measured, the "A" input also has gamma ray pulses from another NaI crystal fed into it. The patch board gate selector is then set with gates on the desired gamma ray peaks, so that as many as eight angular correlations may be measured at the same time.

When gamma ray distributions are measured, where no coincidence is required, the pulses fed into the "B" input bypass the patch board gate selector and enter the pulse-height analyser memory unit directly. The fast timing is ignored and coincidence switches set to anti-coincidence.

A second output of the neutron-gamma ray discriminator yields a pulse representing a count that falls into the neutron peak. These pulses are counted by a scaler and the counts are used to normalize the correlation data.

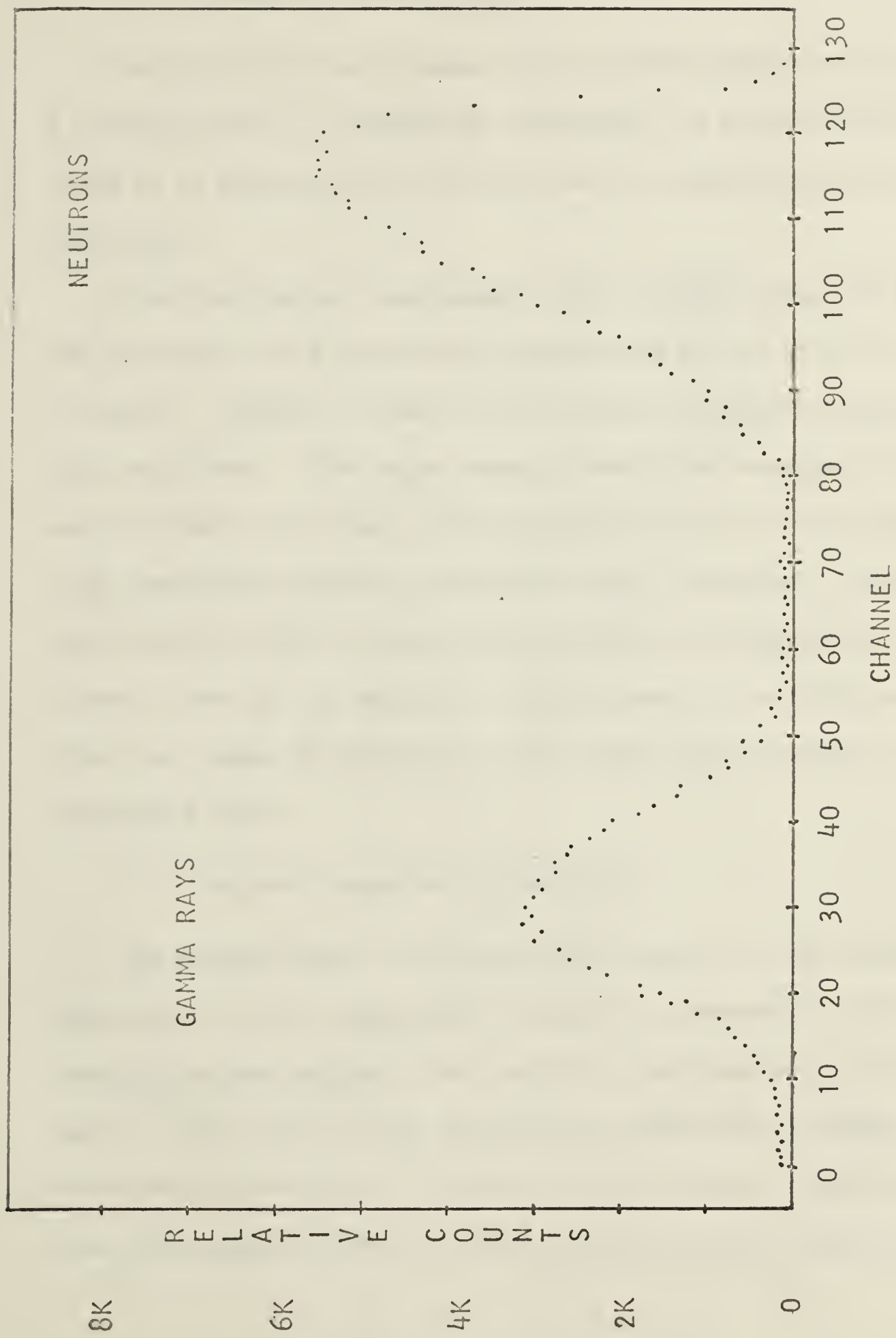


FIG. 2-7 NEUTRON - GAMMA RAY DISCRIMINATOR OUTPUT.

2.2 Experimental Procedure

(a) Gamma-Ray Distributions

The distributions of gamma rays with the neutron unobserved, offers a limited amount of information concerning the nuclear states because there is no predictable restriction on the population of the magnetic substates.

The distribution measurements were obtained using the 3 in. x 3 in. NaI detector, while the neutron counter was placed at -90° to act as a monitor. Figures 2-8 and 2-9 are gamma ray spectra typical of this experiment. They were taken at bombarding energies of 4.43 MeV and 5.50 MeV respectively. The shaded portions are the photo-peak areas used from which relative intensities were calculated. Section 2-3 describes how this was done and the necessary corrections. Beam currents were in the range of 1-1/2 microamperes and typical running times were about 10 minutes for each angle with each angle being repeated 3 times.

(b) Neutron- Gamma-Ray Correlations

The neutron gamma ray correlations consist of the intensity distribution of the gamma rays detected in coincidence with neutrons detected at zero degrees with respect to the beam axis. The counting rate is lower than for the distribution measurements because of the coincidence conditions. The center of the neutron counter was 12.7 cm. from the target spot with the axis of the stilbene crystal at right

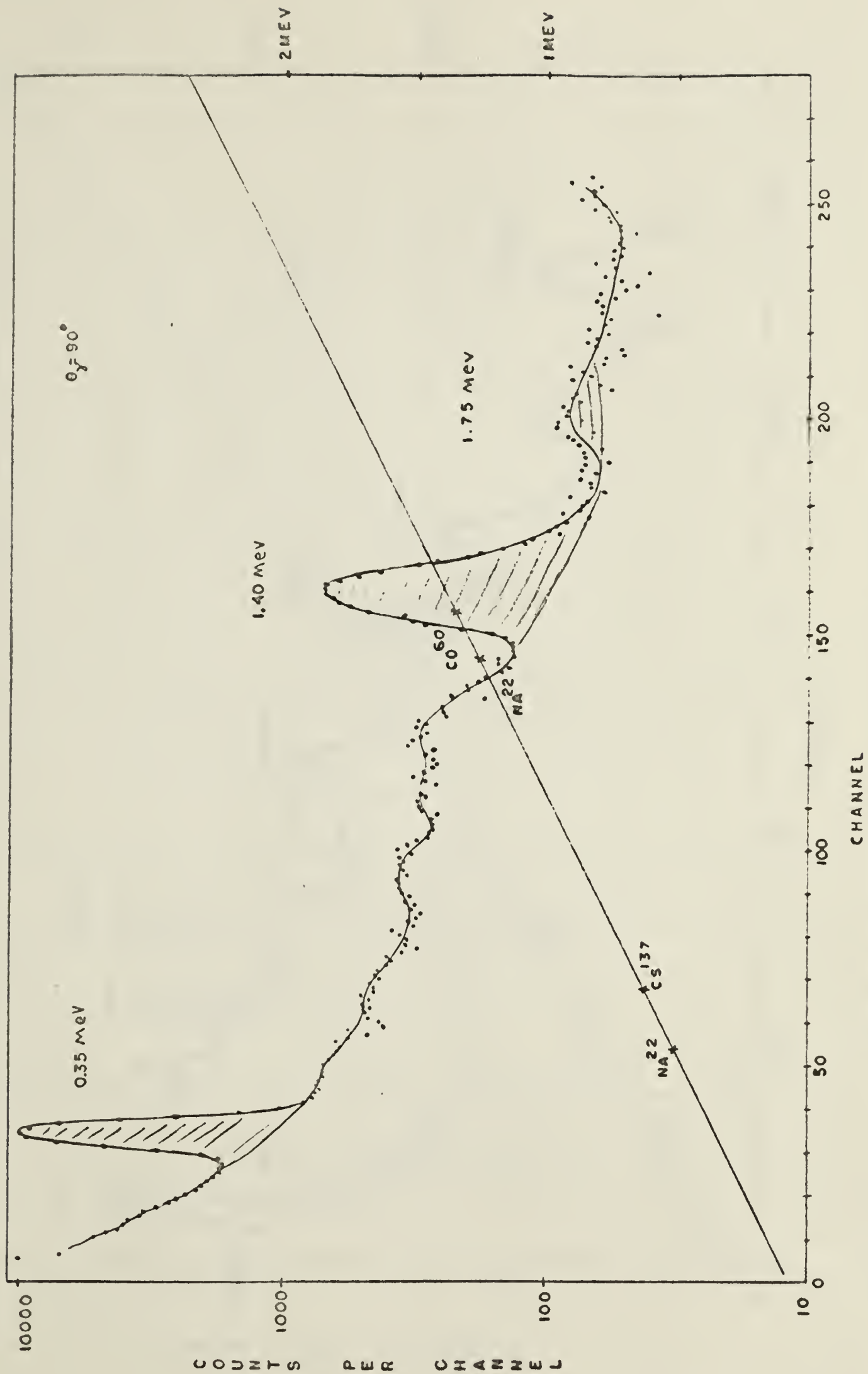


FIG. 2-8 A GAMMA RAY DISTRIBUTION SPECTRUM AT 4.43 MEV BOMBARDING ENERGY.

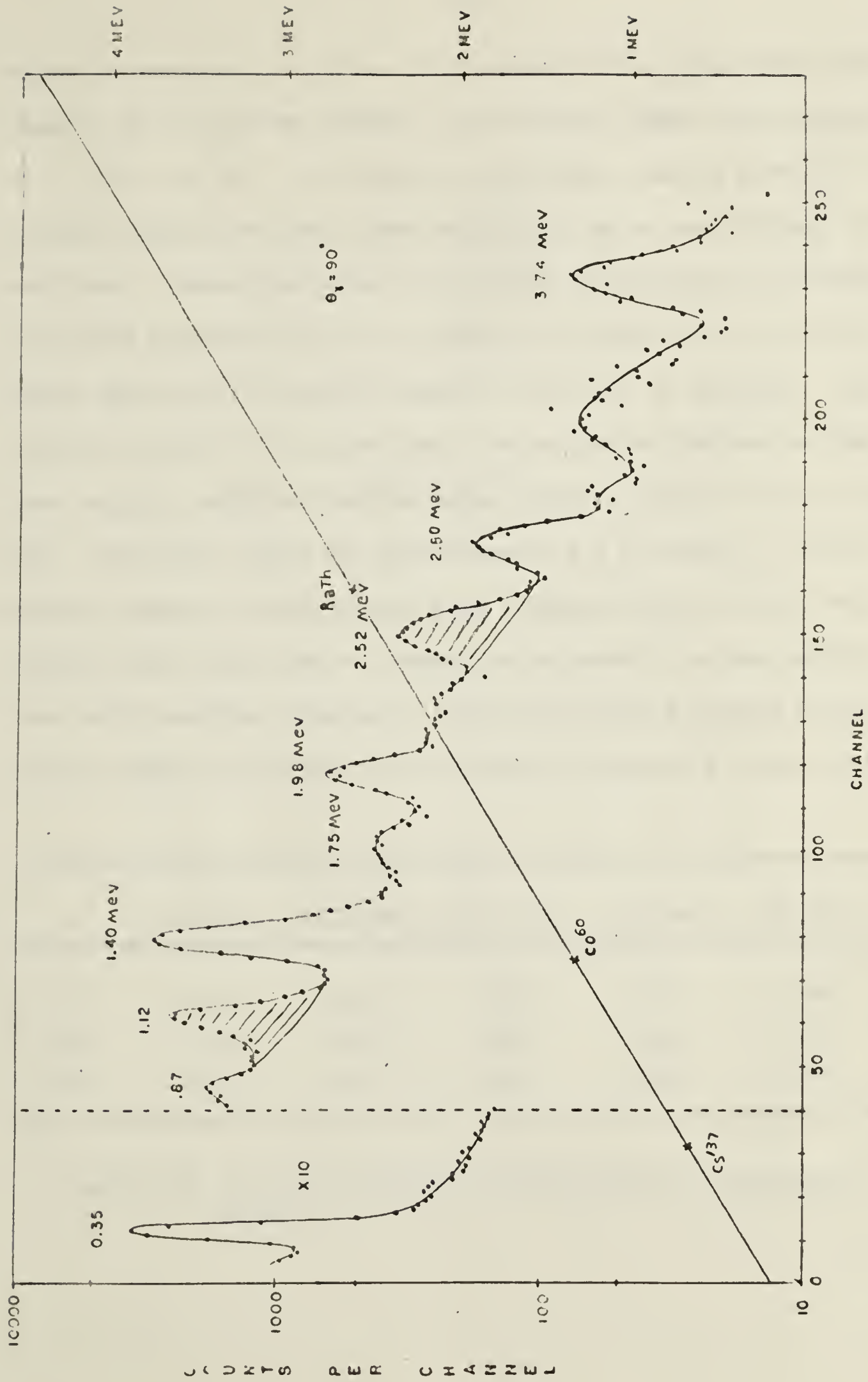


FIG. 2-9 A GAMMA RAY DISTRIBUTION SPECTRUM AT 50 MEV BOMBARDING ENERGY.

angles to the beam direction. This destroyed the cylindrical axial symmetry of the neutron counter, but permitted gamma detector positions of 0° , 15° , and 30° . An absorption correction must be made for the stilbene crystal when the gamma ray counter is in one of these three positions. Correction factors were found by performing an elementary absorption experiment; that is, noting the gamma counts in the full energy peak with the neutron counter in and out of position. This resulted in Table 2.2, which lists the correction factors for the three angular positions and the gamma rays considered in this experiment. The beam current was approximately 1.5 microamps. In the neutron- gamma-ray correlations both integrated beam current and neutron counts were used as normalization factors for the correlations with excellent agreement. Gamma ray spectra typical of the neutron gamma ray correlations are shown in Figures 2-10 and 2-11.

	0.35 MeV	1.12 MeV	1.40 MeV	1.75 MeV	2.52 MeV
0°	1.41	1.15	1.10	1.05	1.00
15°	1.20	1.08	1.03	1.01	1.00
30°	1.01	1.00	1.00	1.00	1.00

Table 2.2 Correction Factors for Absorption in the Neutron Counter

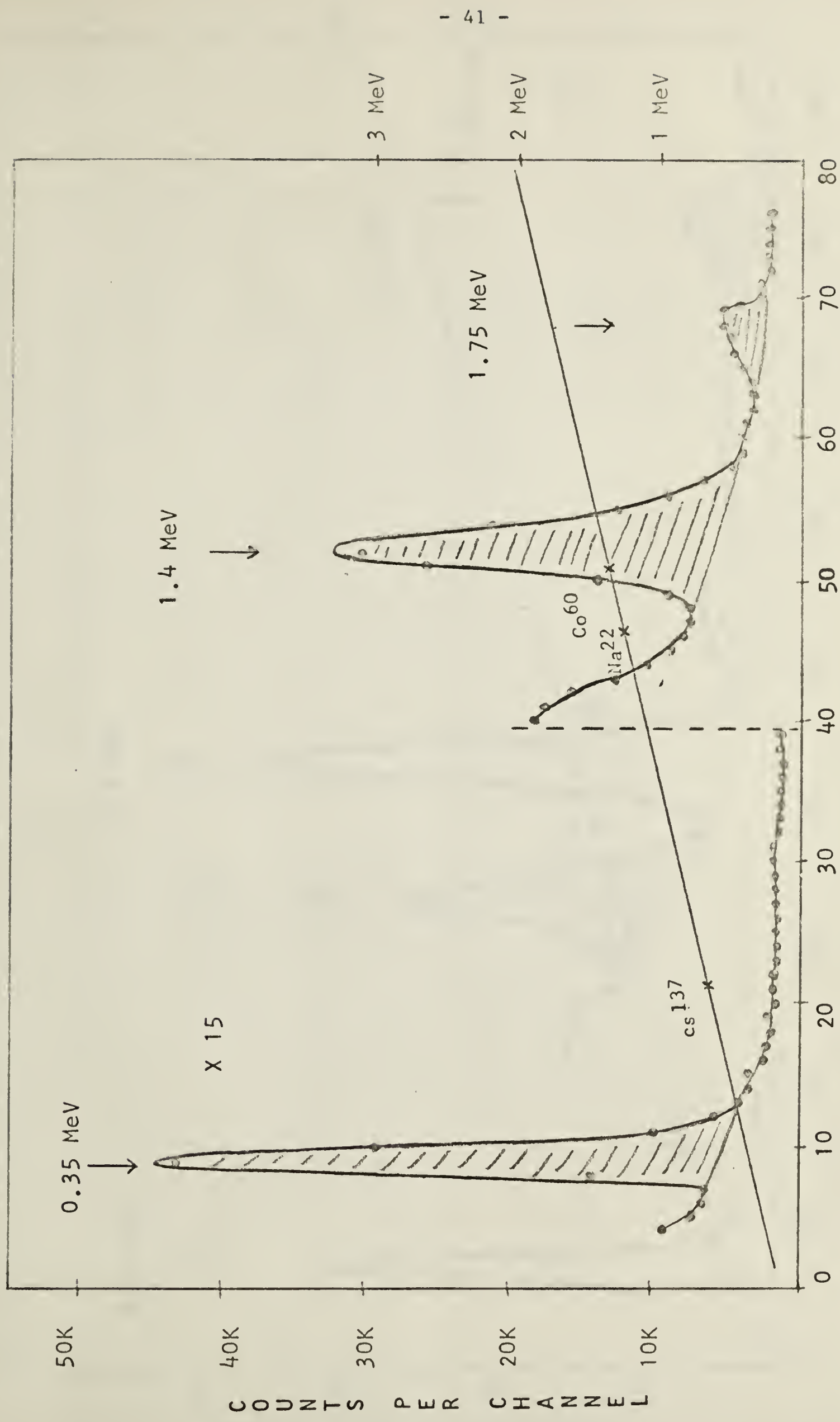


FIG. 2-10 NEUTRON GATED GAMMA RAY SPECTRUM AT THE 4.43 MeV RESONANCE.

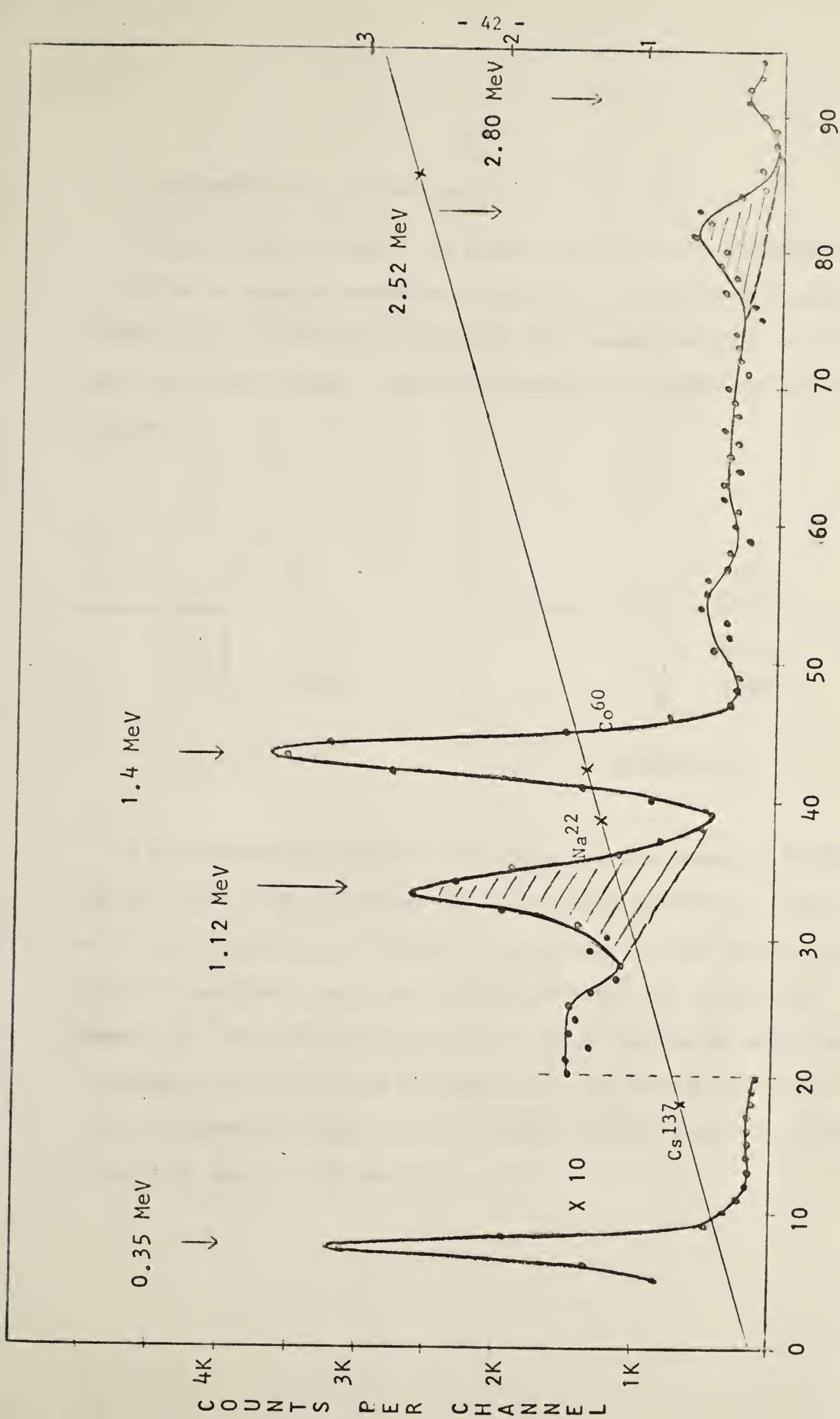
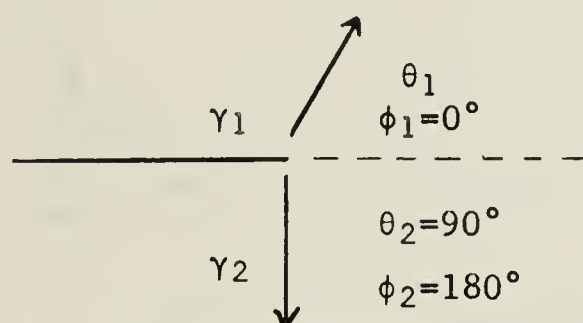


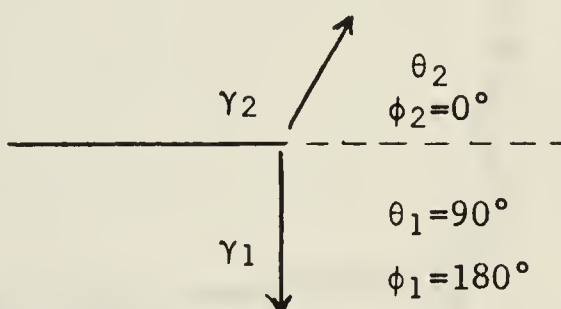
FIG. 2-11 NEUTRON GATED GAMMA RAY SPECTRUM AT THE 5.5 MeV RESONANCE.

(c) Gamma-Gamma Correlations

This experiment involved two gamma ray counters for the coincidence work while the neutron counter was placed at -135° for normalization purposes only. A 1-3/4 in. x 1-1/2 in. NaI counter was free to rotate about the target chamber. With this arrangement two geometries were obtained.



Geometry I



Geometry II

A gamma-gamma correlation of this kind had been measured for the 0.35 MeV and 1.40 MeV gamma rays at the 4.43 MeV resonance. Figure 2-12 is an illustration of typical spectra taken for the two geometries. The first spectrum is gated by the 0.35 MeV gamma ray and is from geometry II. The small 0.35 MeV peak is due to the random counts and the Compton tail of the 1.40 MeV gamma ray. The second spectrum is typical of geometry I and contains only the 0.35 MeV gamma ray which is gated by the 1.40 MeV gamma ray.

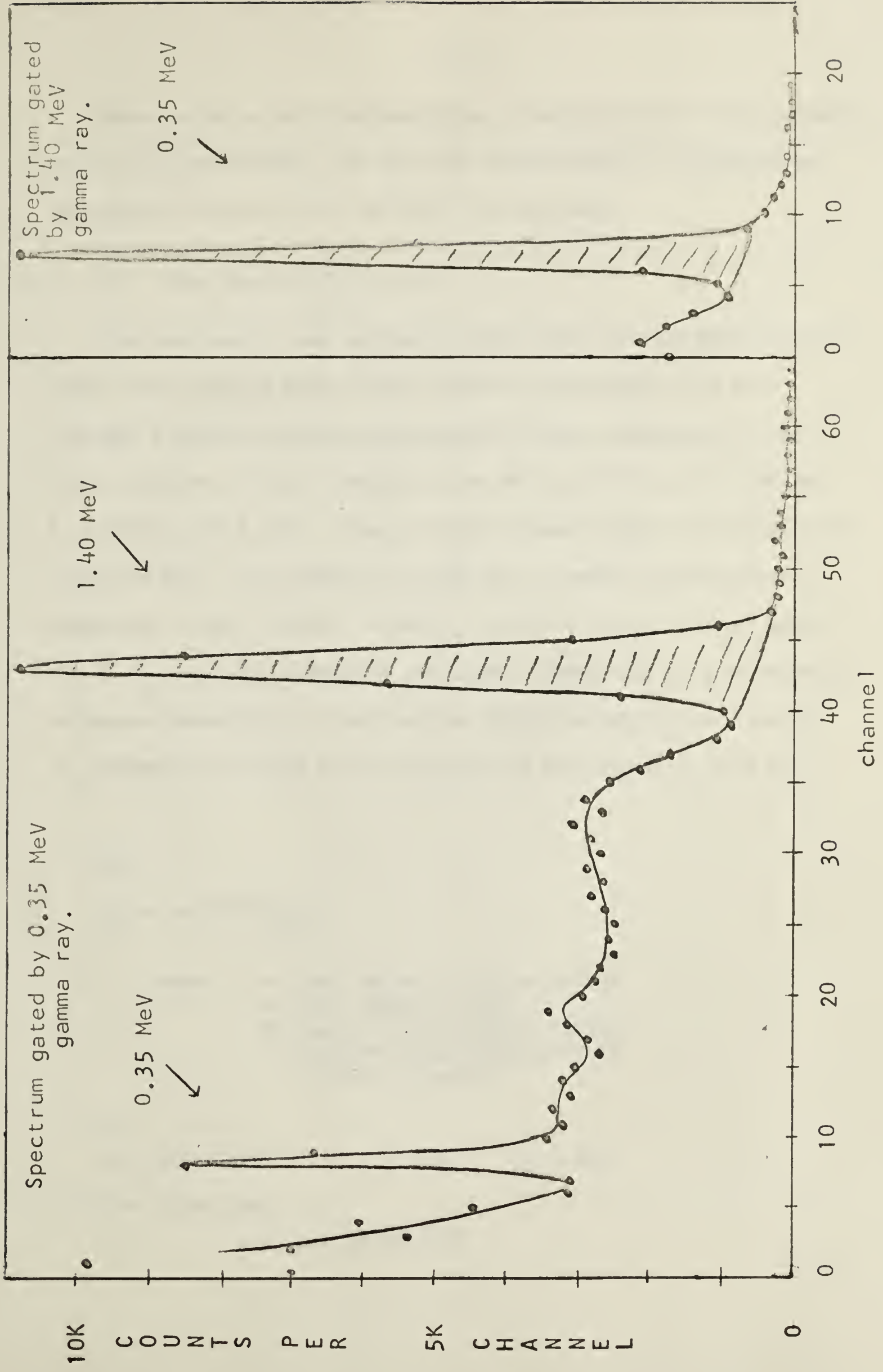


FIG. 2-12 Spectra for gamma-gamma correlations.

Beam currents for this experiment averaged about 1.5 microamperes and the neutron counter was used for normalizing the correlations. Collection time was about one-half hour per angle.

(d) Beam Energy Calibration

The beam energy was calibrated using the reaction $\text{Mg}^{24}(\alpha, \gamma)\text{Si}^{28}$. Some recent work by Rytz, Staub, Winkler, and Zamboni (Ry 63) involves a precise energy determination of two resonances in the above reaction. These resonances are at $E_{\alpha} = 2437.4 \pm 1.0$ keV and $E_{\alpha} = 3199.8 \pm 1.0$ keV. Using a 100 microgram target of isotopically separated Mg^{24} , on a backing of .005 in. Au made by the Isotopic Separation Group, Harwell, England, a yield of the 12.70 MeV gamma ray at the 3.20 MeV resonance was taken. Using the nuclear magnetic resonance gaussmeter, a frequency of 30.245 megacycles per second as indicated by Figure 2-13, was found to correspond to 3.20 MeV.

Using

$$E_{\alpha} = (e^2 R^2 \gamma^2 / 2M_{\alpha}) \nu^2$$

where e = the charge of the electron
 R = the magnet radius
 M_{α} = mass of the alpha particle
 γ = nuclear gyromagnetic ratio
 ν = N.M.R. frequency

let

$$k = e^2 R^2 / 2M_{\alpha} \gamma^2 \quad \text{so that} \quad E_{\alpha} = k \nu^2$$

It is found that

$$k = 0.00348 \text{ MeV/MHz}^2$$

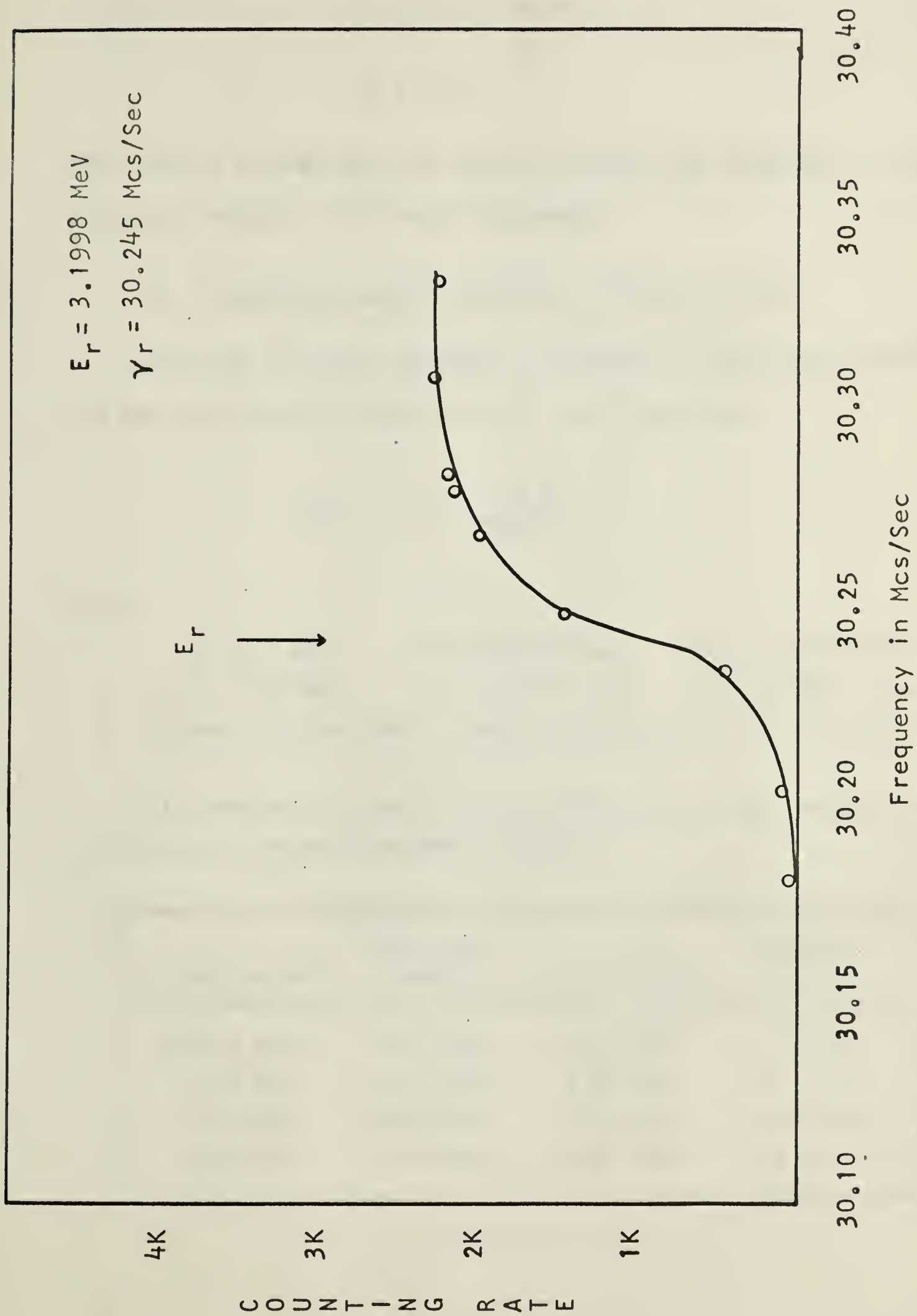


FIG. 2-13 $Mg^{24}(\alpha, \gamma)Si^{28}$ CALIBRATION.

For ΔE and Δv the following equation was used.

$$\Delta E = 2k v \Delta v$$

The constant k found here was used throughout the experiment for determining all energies and energy increments.

(e) Thresholds, Neutron Energies, and Yield Curves

Using the following equation and parameter values the thresholds for the population of levels in Ne^{21} were calculated.

$$E_{th} = -Q \frac{M_1 + M_2}{M_2}$$

where

$$\begin{aligned} Q &= Q_0 - \text{EXN} & M_1 &= 4.003876 \text{ amu} & M_3 &= 1.008986 \text{ amu} \\ Q_0 &= -.705 \text{ MeV} & M_2 &= 18.00667 \text{ amu} & M_4 &= 21.00052 \text{ amu} \\ 1 \text{ amu} &= 931.141 \text{ MeV} & \text{EXN} &= \text{Energy of the excited state.} \end{aligned}$$

This resulted in the following bombarding energies needed for the production of the various levels in Ne^{21} .

Level in Ne^{21}	Threshold Energy	Level in Ne^{21}	Threshold Energy
Ground State	0.861 MeV	2.87 MeV	4.369 MeV
0.35 MeV	1.289 MeV	3.67 MeV	5.347 MeV
1.75 MeV	3.000 MeV	3.74 MeV	5.433 MeV
2.80 MeV	4.284 MeV	3.87 MeV	5.616 MeV

Table 2.3

Using a kinematics program written for the LGP-30 computer at the Nuclear Research Center, the energy of the neutrons emitted at zero degrees was calculated.

At a bombarding energy of 4.43 MeV the neutrons feeding the various levels in Ne^{21} have the following energies at zero degrees:

Level in Ne^{21}	Neutron Energy
Ground State	3.464 MeV
0.35 MeV	3.092 MeV
1.75 MeV	1.558 MeV
2.80 MeV	0.2793 MeV
2.87 MeV	0.1659 MeV

Table 2.4

At a bombarding energy of 5.50 MeV the neutrons have the following energies at zero degrees:

Level in Ne^{21}	Neutron Energy	Level in Ne^{21}	Neutron Energy
Ground State	4.481 MeV	2.87 MeV	1.329 MeV
0.35 MeV	4.109 MeV	3.67 MeV	0.310 MeV
1.75 MeV	2.594 MeV	3.74 MeV	0.193 MeV
2.80 MeV	1.411 MeV	3.89 MeV	-----

Table 2.5

The neutron system was insensitive to neutrons below an energy of approximately 0.50 MeV. This energy was not known precisely.

The level at 3.89 MeV was not formed due to the bombarding energy being below its threshold by 116 keV.

The first experimental undertaking was to determine the yield curves for the gamma rays of interest, in order to know where to expect the maximum yields. Figure 2-14 is the yield of the 0.35 MeV gamma ray and Figure 2-15 is the yield of all neutrons whose energy is above 0.5 MeV. The neutron counter was at 0° for this work, while the 4 in. x 4 in. NaI crystal was at 90° and at a distance of 12 cm. from the target for the gamma ray yield. No formal yield curves were plotted for the other gamma rays, but it should be noted that the 1.40 MeV and 1.75 MeV gamma rays had a maximum yield at 4.43 MeV bombarding energy while the 1.12 MeV and 2.52 MeV gamma rays had a maximum yield at 5.50 MeV bombarding energy. The gamma rays from the 3.67 MeV and 3.74 MeV levels had a maximum at 5.50 MeV also.

The experiment was performed at two bombarding energies. At the 4.43 MeV resonance, neutron gamma ray correlations, gamma ray distributions and gamma-gamma correlations were measured for the gamma rays from the 1.75 MeV and 0.35 MeV levels. This bombarding energy was at an energy of approximately 150 keV above the threshold for the 2.80 MeV but no gamma rays were seen from this level or the 2.87 MeV level. This insured single feeding via the neutrons for the 1.75 MeV level but allowed some double feeding of the 0.35 MeV level. This

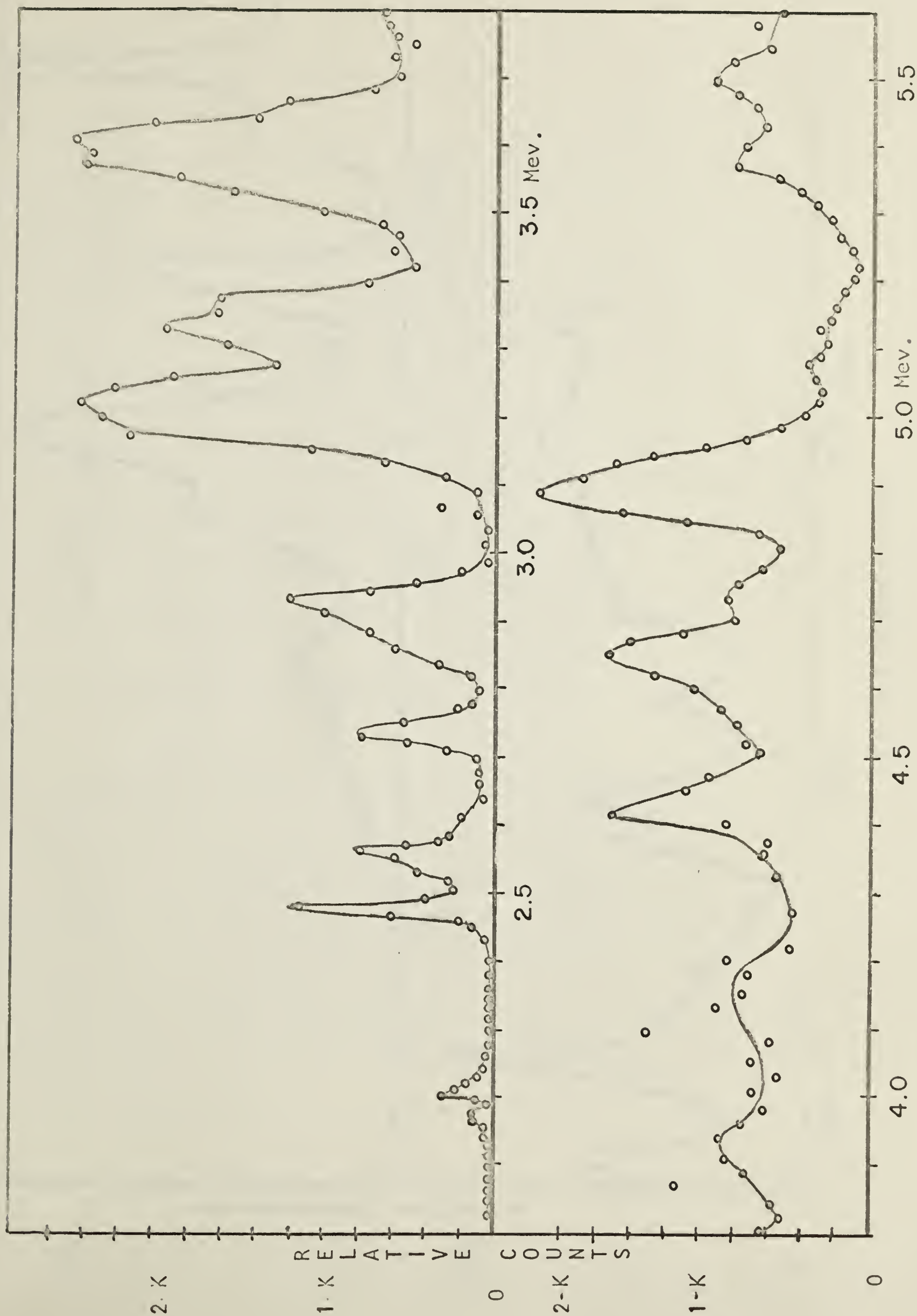


FIG. 2-14 .35 Mev. gamma ray yield.

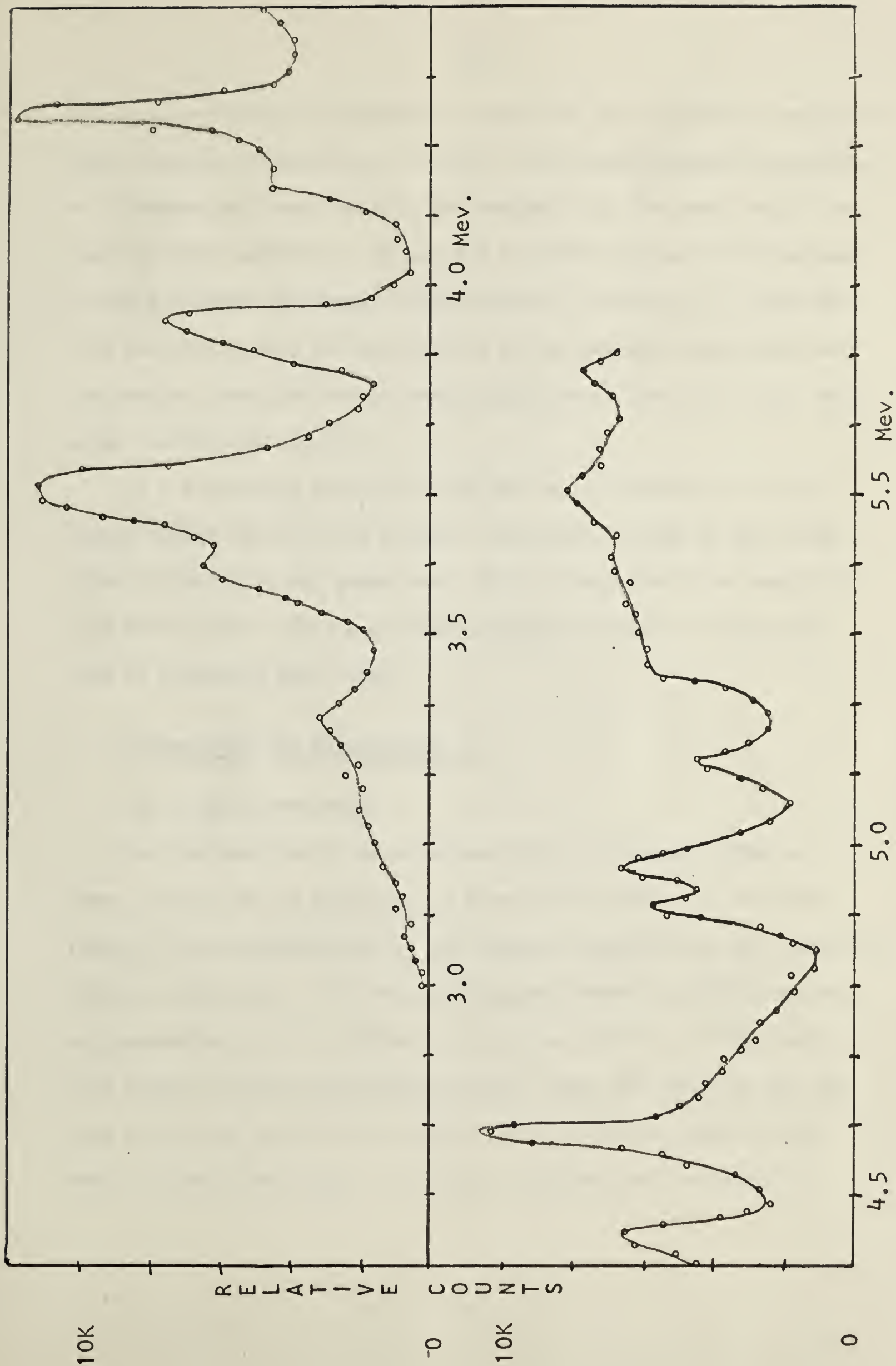


FIG.2-15 NEUTRON YIELD.

effect is considered negligible in this case for the double feeding is small compared to the direct feeding. The neutron-gamma correlations at a bombarding energy of 5.50 MeV yielded only the gamma rays from the 2.87 MeV, 2.80 MeV, 1.75 MeV and 0.35 MeV levels. This was due to the fact that the energy of the neutron feeding the 3.67 MeV and 3.74 MeV levels were 310 keV and 193 keV in energy respectively and the neutron detection system was insensitive to them, i.e. they were below the detector cutoff.

At a bombarding energy of 2.20 MeV one or possibly two unreported levels in Ne^{22} were formed. These can be seen on the yield curve for the 0.35 MeV gamma ray. This corresponds to an energy of 10.4 MeV in Ne^{22} . This experiment provided no way of finding the spin or parity of this level.

2.3 Corrections and Considerations

(a) Fitting Programs

The raw correlation data was analyzed in two ways. One is a least squares fit as described by Rose (Ro 53) where the best fit results in the coefficients of the Legendre polynomials, A_k , and their standard deviations. The Nuclear Research Center's LGP-30 computer was programmed by W. G. Davies to carry out this fit. This program will accept any positive angle between 0° and 180° and will fit the data to any set of five A_k 's from A_0 to A_6 providing there is one more data point than A_k 's. The data is printed out in terms of

unnormalized and normalized coefficients and their standard deviations as well as the best fit value for each of the angles entered. Analysis of the data using these coefficients is outlined in Section 3.1.

The other method of analysis is the χ^2 analysis where χ^2 is a term defining the goodness of a fit.

$$\chi^2 = \sum_i W_i (N_{i\text{fitted}} - N_{i\text{actual}})^2$$

W_i = weight of experimental point

Using this method of analysis one has the advantage of being able to handle a second unknown but, on the other hand, one is not able to give any standard deviation for the unknown parameters. The computer is programmed with equation 2.3 of Section 1.2 and the parameters on which the coefficients are dependent are varied until a minimum is reached in χ^2 . The program was written by Dr. J. M. Kennedy of the Chalk River computer group. The data was sent to Dr. T. K. Alexander who was kind enough to run the data on the Chalk River computer.

(b) Target Backing Correction

Since at certain angles of emission and gamma ray energy the target backing may act as a very strong gamma ray absorber, a correction must be made.

During the experiment the target had two orientations with respect to the beam direction.



In both of these orientations, at various angular positions of the gamma ray counter the gamma ray travels through different backing thicknesses. This is particularly critical for the low energy gamma-rays investigated. Calculations were made to find an average thickness for a particular incident angle with respect to the target plane. This resulted in the following table of attenuation factors for a backing of tantalum of 0.0127 cm. thickness. The appropriate correction was made to the data.

E_{γ}	15°	30°	45°	60°	75°	90°
0.35	0.76	0.86	0.93	0.94	0.95	0.95
0.87	0.83	0.90	0.95	0.96	0.97	0.95
1.12	0.93	0.97	0.97	0.98	0.98	0.97
1.40	0.94	0.98	0.98	0.99	0.99	0.99
1.75	0.94	0.98	0.98	0.99	0.99	0.99
1.99	0.94	0.98	0.98	0.99	0.99	0.99
2.52	0.96	0.97	0.99	1.00	1.00	1.00
3.74	0.97	0.97	0.99	1.00	1.00	1.00

Table 2.6

Target Thickness Corrections

(c) Solid Angle Corrections for Gamma-Ray Detectors

Because the finite angular resolution of a counter tends to flatten the intensity distribution of a gamma ray, a correction must be made. Rose (Ro 53) has developed a method for conveniently correcting the data for this effect.

An experimental distribution may be represented by

$$W(\theta) = 1 + A_2 Q_2 P_2(\cos \theta) + A_4 Q_4 P_4(\cos \theta) + \dots$$

$$\text{where } Q_K = \frac{\int_0^\pi \epsilon(\xi) P_K(\cos \theta) \sin \xi d\xi}{\int_0^\pi \epsilon(\xi) P_0(\cos \theta) \sin \xi d\xi}$$

and $\epsilon(\xi)$ is the efficiency of the counter for a gamma ray moving at an angle ξ to the axis of the counter.

These correction coefficients have been calculated and tabulated for a 3 in. x 3 in. NaI counter by Davisson (Da 64). These calculations were made using the full energy peak efficiency and the results are given in Table 2.7. Using this table the graphs of Appendix C, Figures C-1, C-2, C-3, and C-4, may be plotted. These graphs conveniently give the value of Q_K for a given crystal to target distance and gamma ray energy.

In order to obtain efficiency curves based on the full energy peak, the efficiency curves for a 3 in. x 3 in. crystal given in Nuclear Data Tables, part 3, page 55 (Nu 60) are multiplied by the peak to total ratios of page 59 of the same reference. The resulting graph is given in Figure C-7.

Attenuation coefficients, Q_k , calculated on the assumption that only the full energy peak of the gamma ray is measured. The variables are the gamma ray energy in Mev., E , and the source to crystal face distance, X , in cm. The table is for a 3"x3" NaI detector.

$$Q_k = J_k/J_0 \quad J_k = \int \epsilon(\theta) P_k(\cos\theta) d(\cos\theta)$$

Q_2 E_γ	X			
	4	6	10	15
0.3	0.7208	0.8345	0.9248	0.9626
0.5	0.7565	0.8538	0.9332	0.9663
0.7	0.7682	0.8609	0.9359	0.9673
1.0	0.7749	0.8654	0.9375	0.9677
1.5	0.7793	0.8687	0.9388	0.9681
2.0	0.7822	0.8706	0.9398	0.9686
3.0	0.7877	0.8737	0.9419	0.9697
5.0	0.7986	0.8790	0.9456	0.9717
7.0	0.8080	0.8835	0.9485	0.9732
10.0	0.8186	0.8886	0.9513	0.9745
15.0	0.8293	0.8943	0.9533	0.9750
20.0	0.8337	0.8973	0.9533	0.9740

Q_4 E_γ	X			
	4	6	10	15
0.3	0.2806	0.5229	0.7649	0.8795
0.5	0.3576	0.5736	0.7895	0.8898
0.7	0.3828	0.5918	0.7976	0.8933
1.0	0.3972	0.6035	0.8024	0.8957
1.5	0.4071	0.6120	0.8063	0.8978
2.0	0.4140	0.6172	0.8093	0.8994
3.0	0.4274	0.6258	0.8151	0.9025
5.0	0.4533	0.6409	0.8256	0.9076
7.0	0.4753	0.6534	0.8338	0.9113
10.0	0.5000	0.6677	0.8423	0.9150
15.0	0.5242	0.6828	0.8494	0.9176
20.0	0.5339	0.6905	0.8507	0.9174

This data was obtained from reference (Da64).

TABLE 2.6

In all of the illustrations of the measured distributions and neutron- gamma-ray correlations the quoted coefficients have been corrected for the finite solid angle of the gamma ray counter. In the gamma-gamma correlations, the effect of the finite solid angle is corrected during the calculations, and thus the quoted coefficients in Figure 3-25 are not corrected for the solid angle.

The correction factors for the 1-3/4 in. x 1-1/2 in. crystal, based on the full energy peak, were not available and an approximation for their values had to be made. Nuclear Data Tables, part 3 (Nu 60) have curves for this correction, based on the full energy spectrum for a 1-3/4 in. x 2 in. crystal and a 3 in. x 3 in. crystal. The method of approximation entails using the ratio of the 3 in. x 3 in. values of Q_K , based on full energy peak, to the value based on total energy spectrum for a target to detector distance equivalent to that which gives the same solid angle for the 1-3/4 in. x 1-1/2 in. detector. Using a 6.5 cm. target to detector distance for the small crystal produces approximately the same solid angle as 10 cm. for a 3 in. x 3 in. detector.

Using Figures C-3 and C-4 in Appendix C and the curves given in the Nuclear Data Tables, pages 73 and 75, the following ratios were calculated. For a target to detector distance of 10 cm:

	0.35 MeV	1.40 MeV	1.75 MeV
$Q_2\text{Peak}/Q_2\text{Total}$	1.003	1.008	1.010
$Q_4\text{Peak}/Q_4\text{Total}$	1.020	1.026	1.031

The values of Q_K given on pages 69 and 71 of the Nuclear Data Tables may be modified by the above factors giving:

0.35 MeV		1.40 MeV		1.75 MeV		
$h_{cm.}$	Q_2	Q_4	Q_2	Q_4	Q_2	Q_4
3	0.8084	0.4700	0.8328	0.5220	0.8356	0.5280
5	0.9106	0.7310	0.9233	0.7600	0.9254	0.7660
7	0.9489	0.8490	0.9591	0.8670	0.9612	0.8720
10	0.9737	0.9250	0.9816	0.9380	0.9837	0.9420

h = detector to target distance

These values may be plotted giving Figures C-5 and C-6 in Appendix C. This approximation is most reliable near 6.5 cm. The values for a 1-3/4 in. x 1-1/2 in. detector are slightly larger than those given in Figures C-5 and C-6 for a 1-3/4 in. x 2 in. detector, but this difference is smaller than the error introduced in the approximation.

CHAPTER III. ANALYSIS AND DISCUSSION

3.1 The 0.35 MeV Level

The angular momentum properties of the 0.35 MeV level were studied in two ways. One, called an n- γ correlation, is the intensity distribution of the 0.35 MeV gamma ray with respect to the neutrons emitted at zero degrees. The other method is the gamma-gamma correlation which is described in part C of Section 3.2. In the n- γ correlation it may be assumed the magnetic substates predominantly populated are $m = \pm 1/2$. This is because of the geometry employed and has been discussed in Section 1.2. Because the neutron counter used has poor angular resolution as compared to an infinitely small counter, the magnetic substates $m = \pm 3/2$ may also be weakly populated. The population parameter $P(m)$, the relative probability of a substate being populated is comparatively small for the $m = \pm 3/2$ substates.

The n- γ correlation was measured at a bombarding energy of 4.43 MeV and three separate measurements were made. Each of these measurements consists of a repetition of all angles in a random order as is true of all the correlation and distribution measurements described in this thesis. The three separate measurements were combined in two ways. One is by performing a least squares fit of each measurement individually and then averaging the coefficients to get a final set of coefficients. The other method is to add the counts in each of

the three separate measurements giving one correlation and then performing a χ^2 analysis. Figure 3-1 illustrates the three correlations after all corrections, except for the finite solid angle of the gamma ray counter, have been made. The solid line is the least squares fit and the error bars are the same size as the circles representing the points. The quoted coefficients have been corrected for the finite solid angle of the counter.

In the analysis of all the n - γ correlations in this Chapter, the experimental coefficients are compared to the predicted coefficients assuming $P(1/2)$ as the only non-zero population parameter. After this has been done, the possibility of there being some contribution from the $m = \pm 3/2$ substates is considered. This is done by examining the change in the predicted correlation as $P(3/2)$ becomes non-zero.

Using the equations of Appendix A with the assumption that $P(1/2)$ is the only non-zero population parameter, a plot of A_2 and A_4 versus δ may be made. This is a convenient way of illustrating how well a particular spin combination fits a correlation. By indicating the range of the measured A_2 and A_4 coefficients on these graphs the possible range of δ is graphically illustrated for a particular spin combination. Figure 3-3 is typical.

If a spin of $1/2$ is assumed for the 0.35 MeV level, then any gamma ray emitted from it must have an isotropic correlation. The average of the three measurements for the 0.35 MeV gamma ray gives

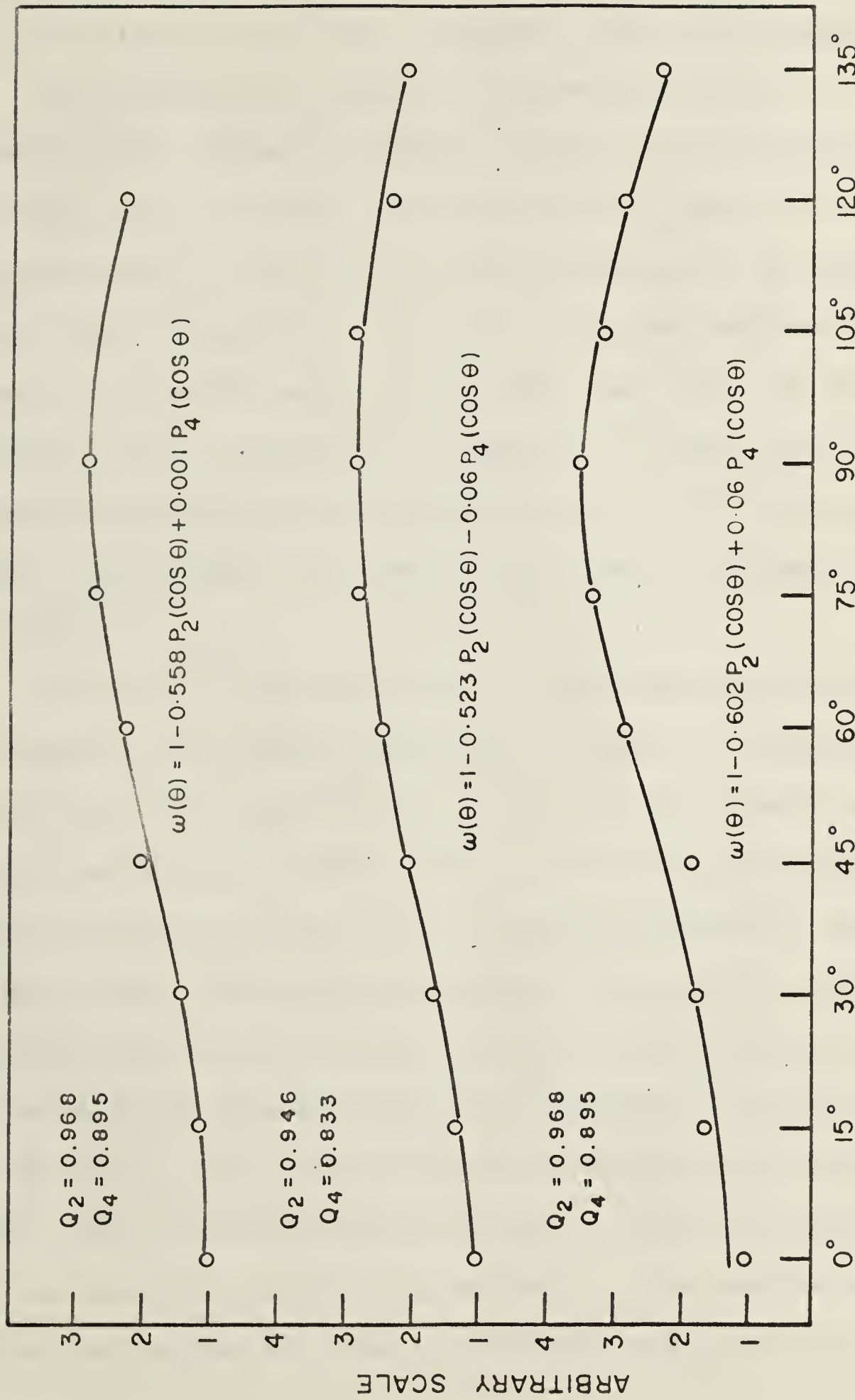


FIG. 3-1 THE MEASURED NEUTRON-GAMMA RAY CORRELATIONS OF THE 0.35 MEV GAMMA RAY AT A BOMBARDING ENERGY OF 4.43 MEV.

the following coefficients, $A_2 = -0.561 \pm 0.02$ and $A_4 = + 0.001 \pm 0.003$.

It is far from isotropic and eliminates a spin of $1/2$ immediately.

For the remaining analysis it must be assumed that the ground state is $3/2$. Evidence to support this was shown in Section 1.3. Assuming that the 0.35 MeV level has spin $3/2$, the graph in Figure 3-2 may be plotted. This graph is based on equation A-1 of Appendix A for a spin combination of $3/2$ to $3/2$. The graph indicates that the predicted A_2 coefficient has the correct sign but is too small in magnitude and an examination of equation A-1 reveals that the predicted correlation tends towards isotropy as $P(3/2)$ departs from zero. This evidence indicates that this level is probably not $3/2$ in spin.

A $5/2$ to $3/2$ combination does predict a correlation which is in the range of the measured coefficient. Figure 3-3 illustrates how well the A_2 and A_4 coefficients fit for this spin combination. A small contribution of $P(3/2)$ would tend to flatten the predicted correlation slightly and a larger δ would be required to maintain the same agreement with the measured value. Figure 3-4 is a plot of δ versus $P(3/2)/P(1/2)$, indicated henceforth as $P'(3/2)$, which is needed to maintain the agreement between the measured and predicted values of A_2 and A_4 . This graph is made by equating the upper limit and lower limit of the measured coefficients to the coefficients predicted by the correlation equations in Appendix A. The resulting equations, which have the two variables δ and $P'(3/2)$, are then plotted. That a

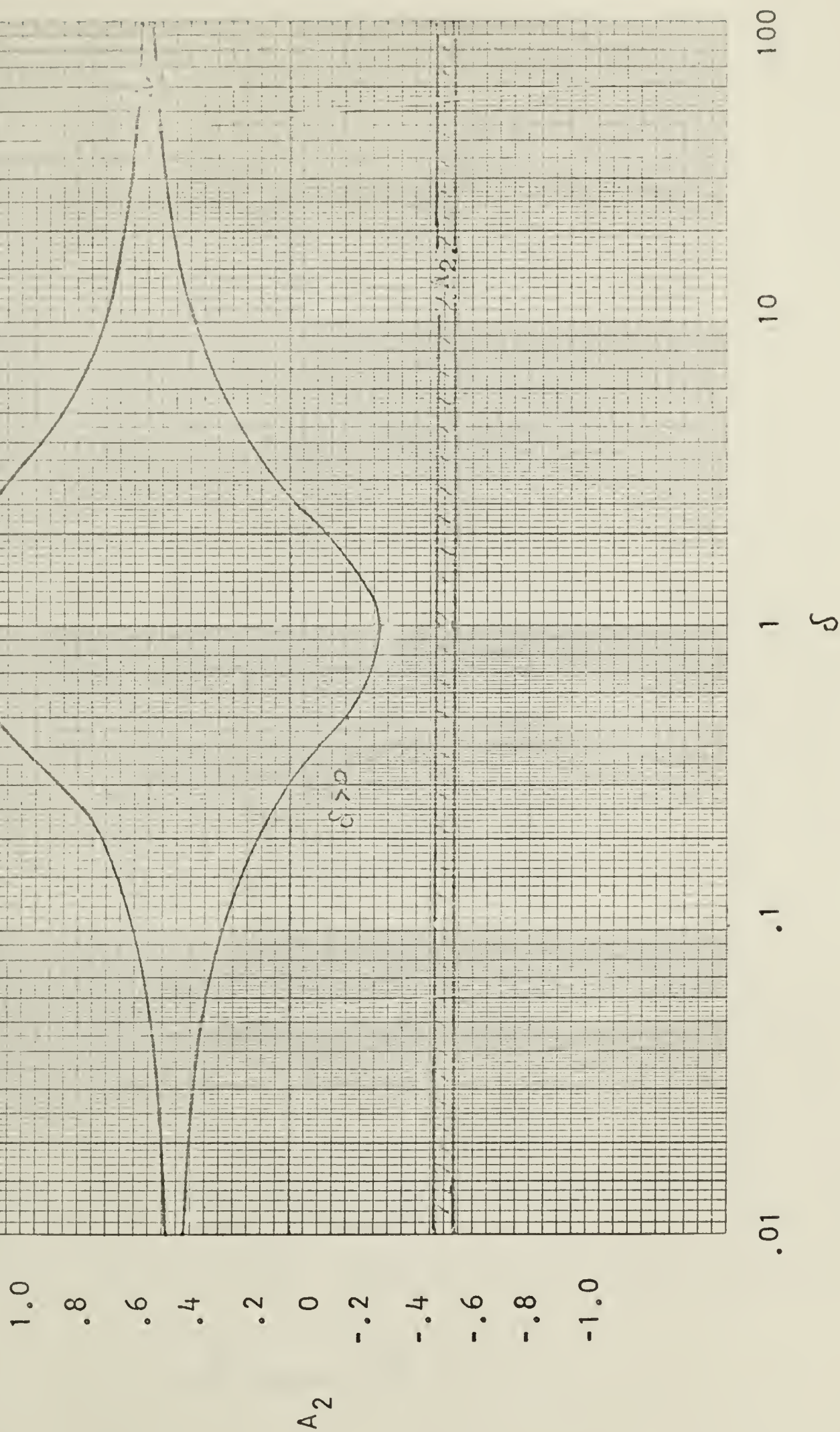


FIG. 3-2

A PLOT OF A_2 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $3/2$ TO $3/2$. THE SHADED BAR IS THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 COEFFICIENT FOR THE 0.35 MEV GAMMA RAY. NO A_4 IS PREDICTED.

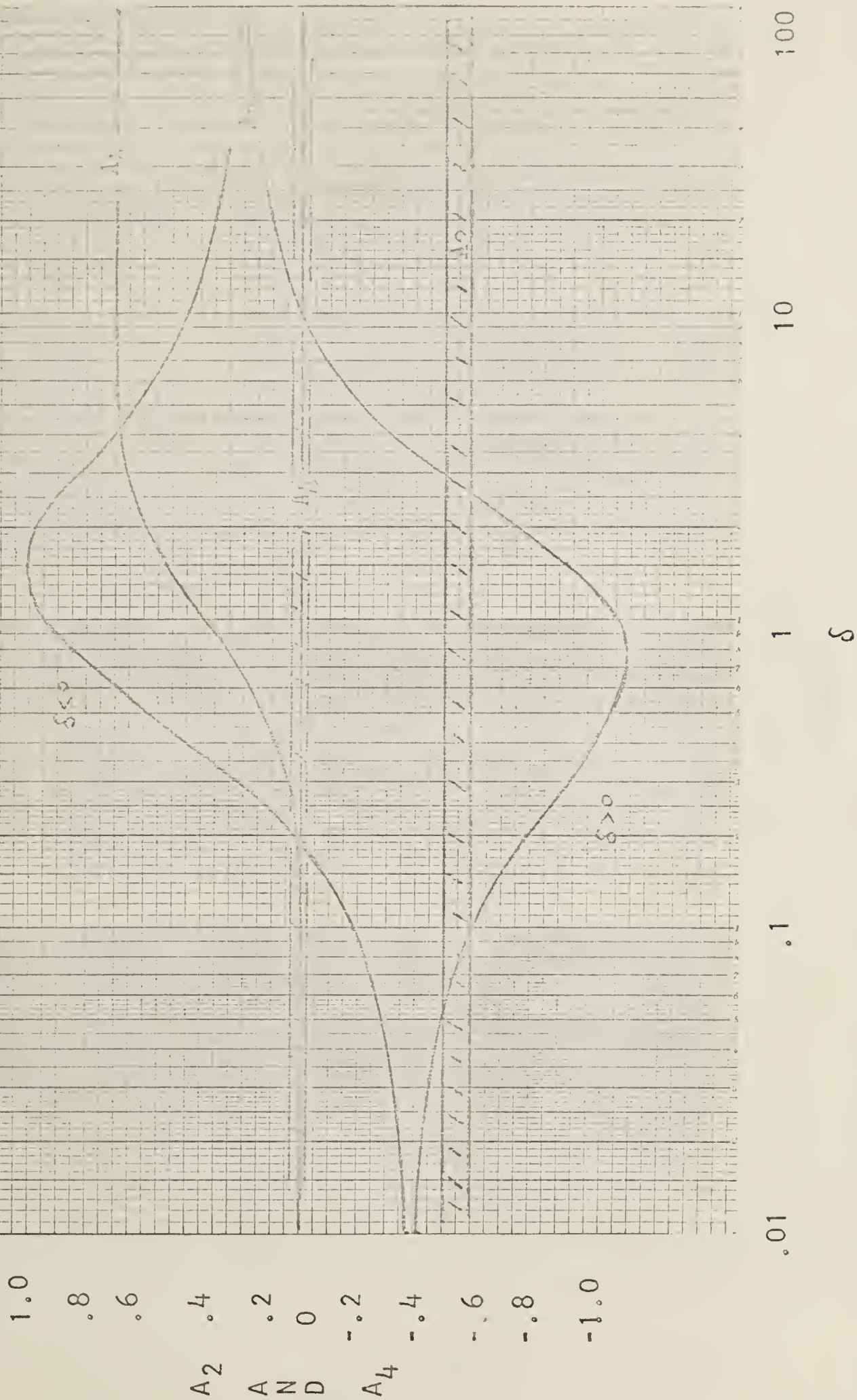


FIG. 3-3 A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $5/2$ TO $3/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 0.35 MEV GAMMA RAY.

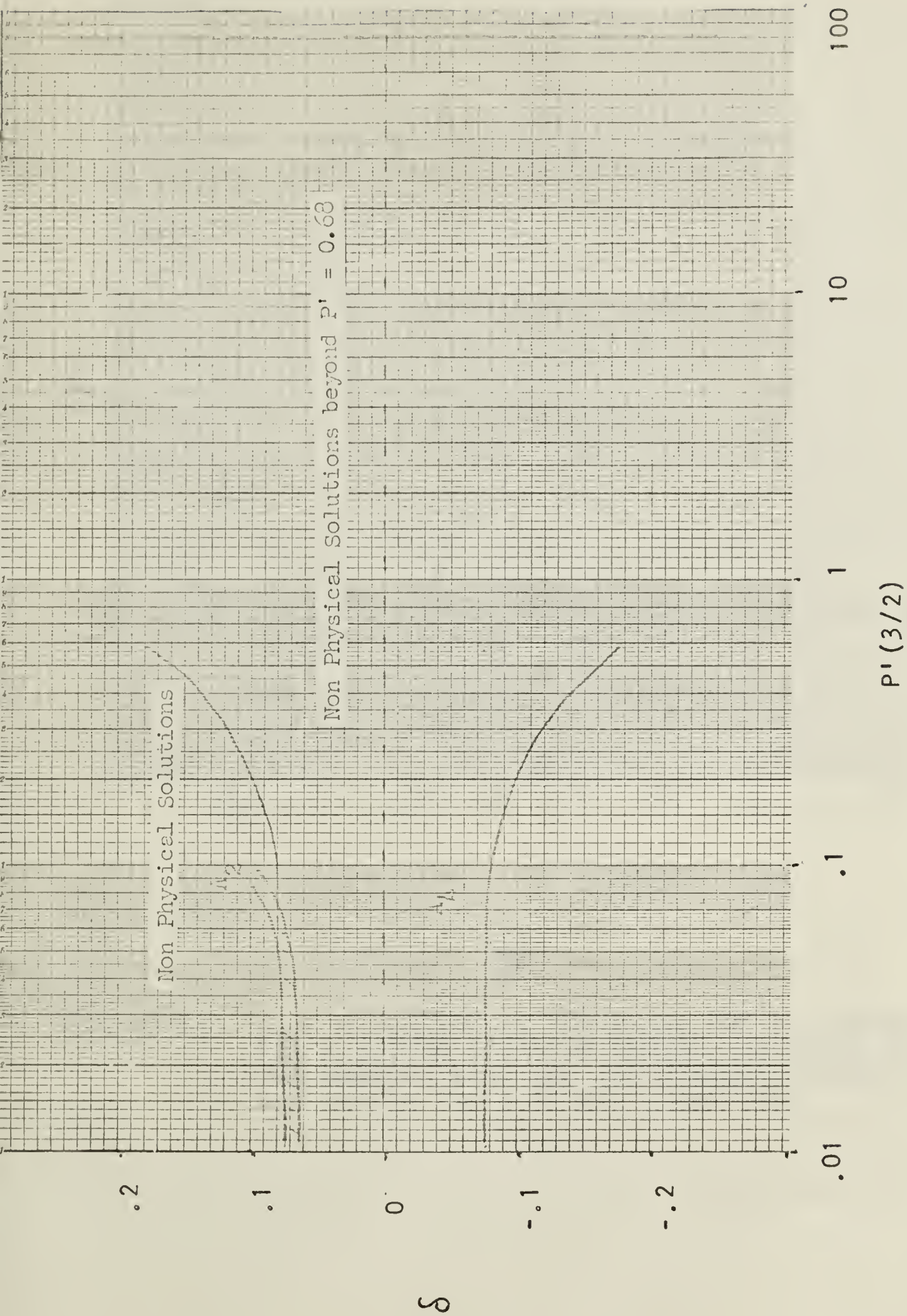


FIG. 3-4 A PLOT OF δ VERSUS $P'(3/2)$ USING THE MEASURED VALUES OF A_2 AND A_4 FOR THE 0.35 MEV GAMMA RAY AND THE PREDICTED COEFFICIENTS FOR A $5/2$ TO $3/2$ SPIN CHANGE.

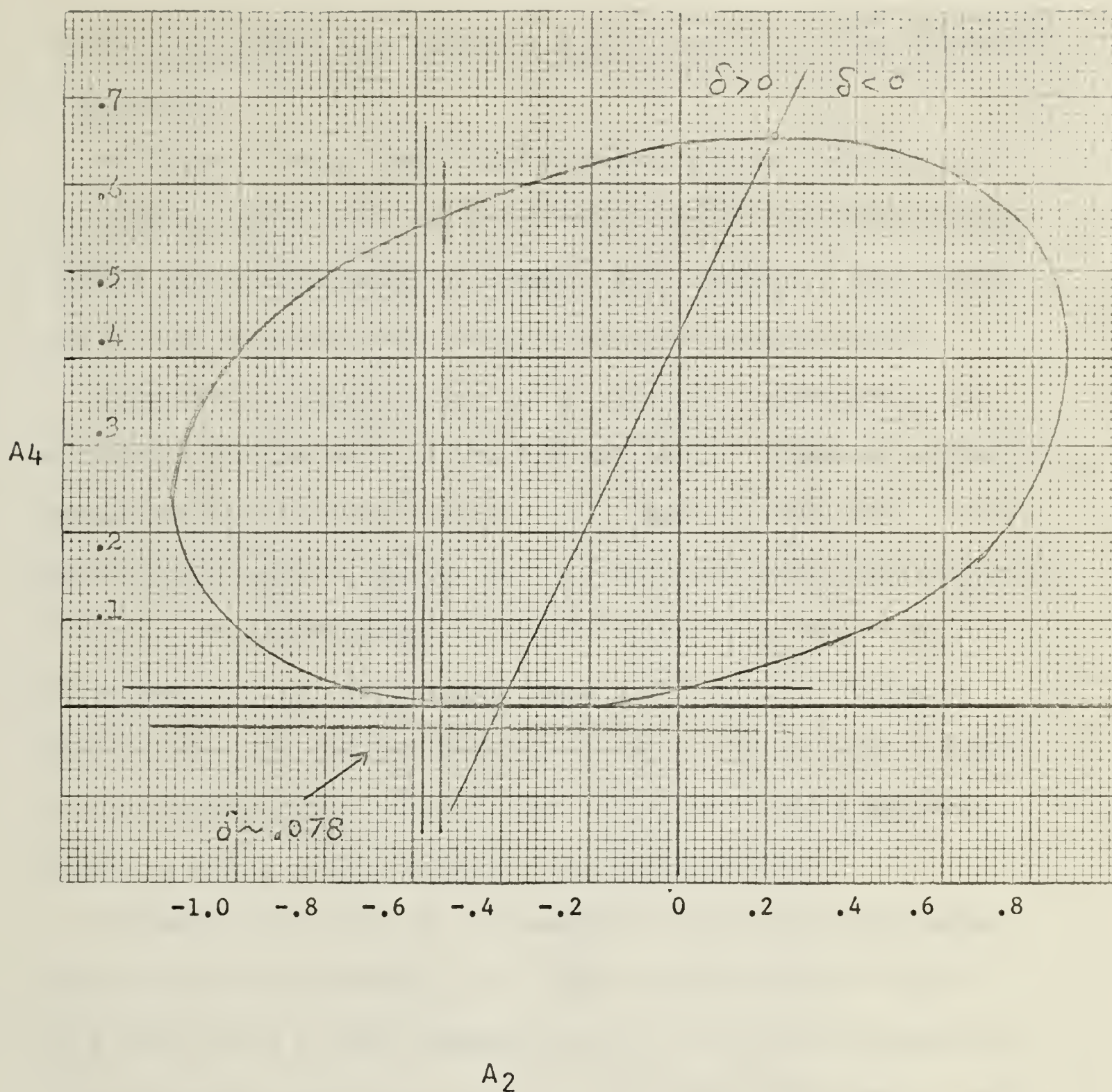


FIG. 3-5

A PLOT OF A_2 VERSUS A_4 FOR ALL VALUES OF δ FOR A $5/2$ TO $3/2$ SPIN CHANGE, ASSUMING ONLY $P(\frac{1}{2})$. THE CROSSED BARS ARE THE MEASURED VALUES OF A_2 AND A_4 FOR THE 0.35 MEV GAMMA RAY.

contribution greater than $P'(3/2) = 0.07$ is not possible is indicated by Figure 3-4.

A $7/2$ to $3/2$ spin combination is definitely not possible as is indicated by Figure 3-6. The predicted A_2 coefficient never becomes negative and an examination of equation A-8 indicates a contribution from $P'(3/2)$ would not make the A_2 coefficient negative either.

This analysis shows that a $5/2$ to $3/2$ spin combination is the most likely for the decay of the 0.35 MeV level. Since the predicted correlation equations are quadratic in δ , two solutions exist. The most probable value of the two can be found graphically from Figure 3-5 which is a plot of A_2 versus A_4 for all values of δ from $-\infty$ to $+\infty$. The crossed bars are the measured range of A_2 and A_4 . This plot indicates that the smaller value of the two δ 's is the most probable value since the larger value does not allow simultaneous agreement between A_2 and A_4 . This value of δ is $+0.082 \pm 0.015$.

Figure 3-7 is a plot of a χ^2 analysis of the sum of the three correlations given in Figure 3-1. This analysis yields a best fit for a value of $\delta = +.084$ assuming that only $m = \pm 1/2$ is populated. The other minimum occurs at about $\delta = 1.73$ which corresponds to the second solution of the quadratic equation from the predicted A_2 .

The distribution of the 0.35 MeV gamma ray does not yield any valuable information directly, since there are too many unknowns introduced by there not being any predictable limitation on the population parameters. The distribution would have to include the

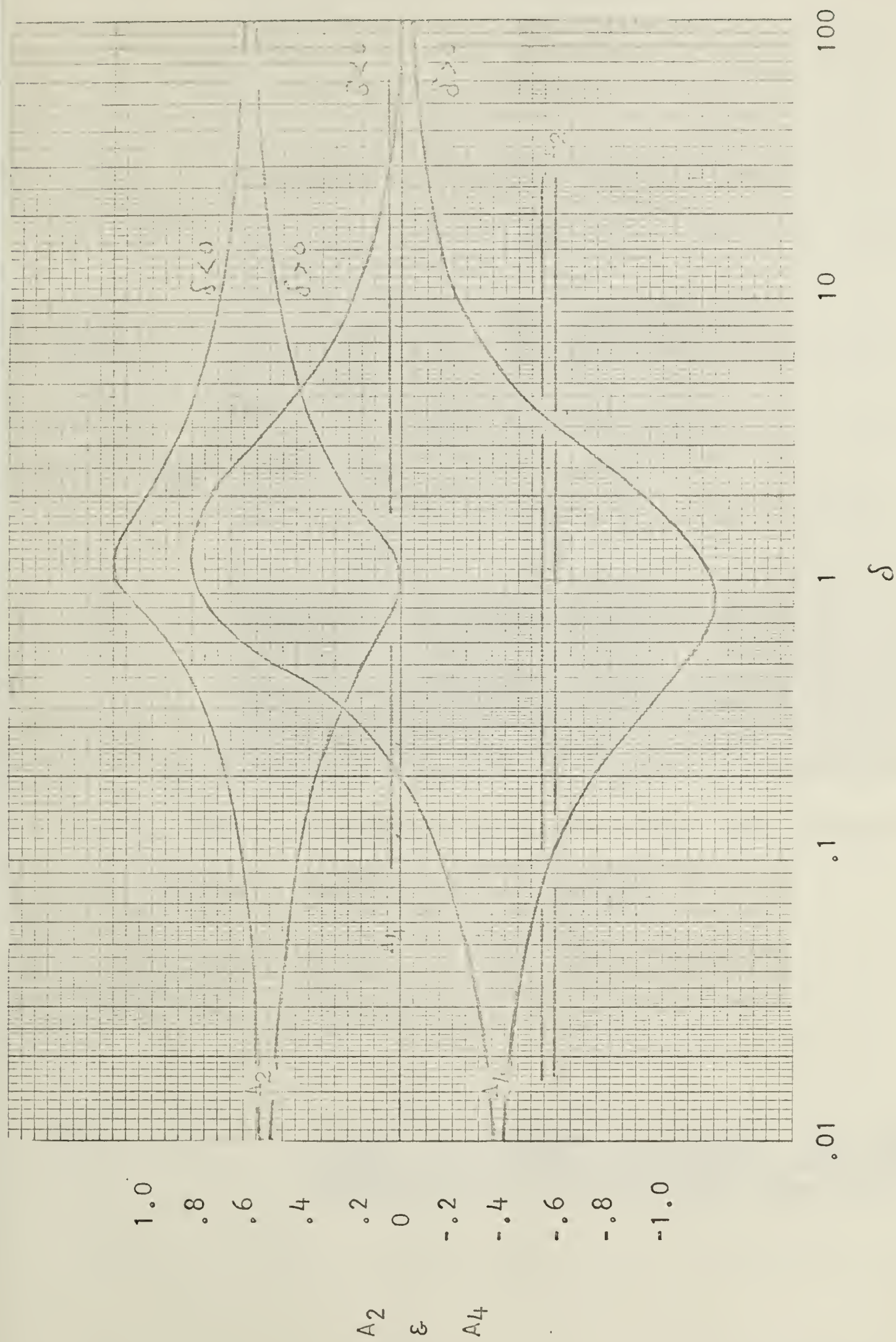


FIG. 3-6 A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $7/2$ TO $3/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 0.35 MEV GAMMA RAY.

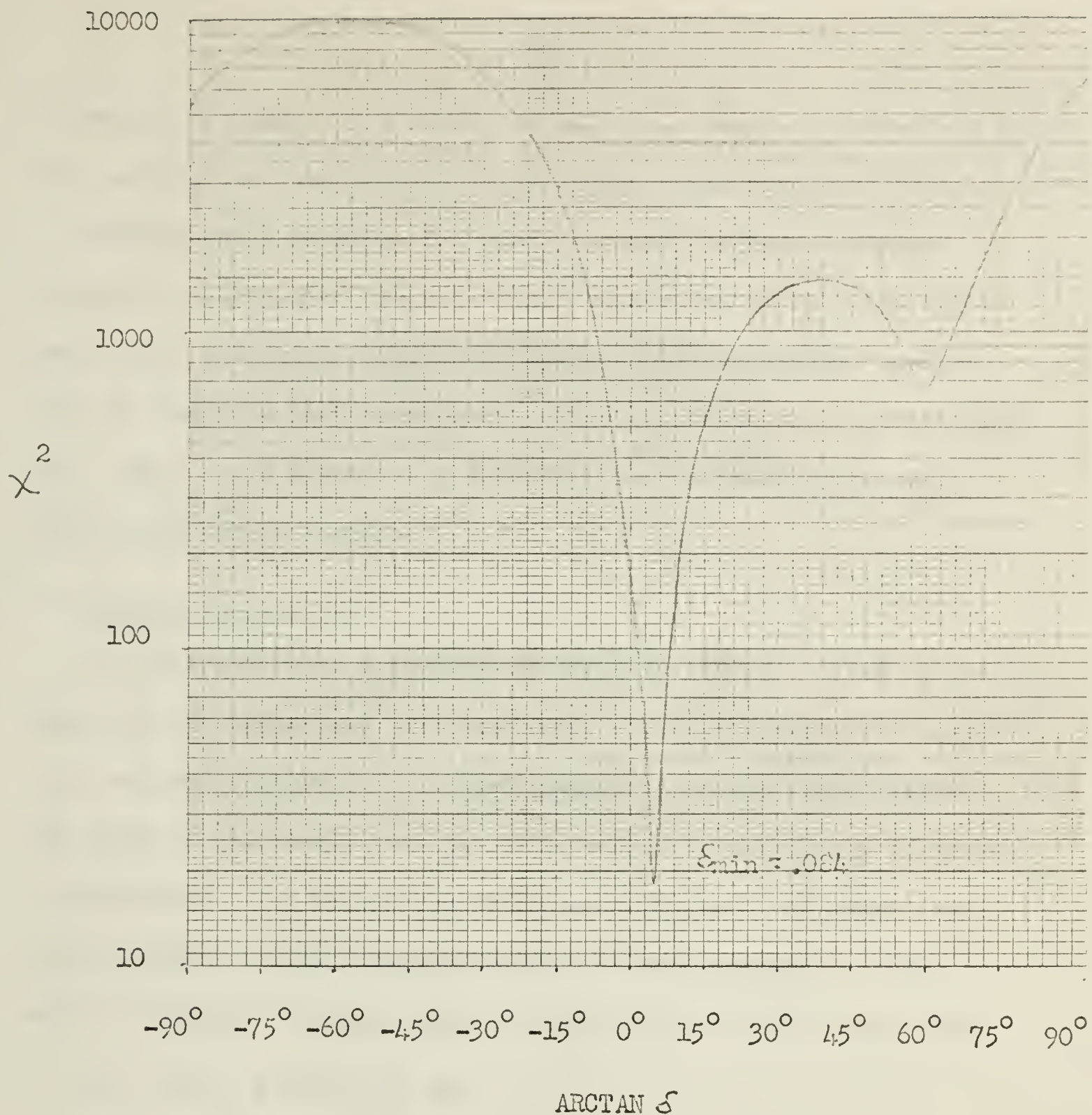


FIG. 3-7

A PLOT OF χ^2 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ AND USING A 5/2 TO 3/2 SPIN CHANGE WITH THE N-GAMMA CORRELATION OF THE 0.35 MEV GAMMA RAY.

following unknowns, δ , $P^i(3/2)$, $P^i(5/2)$, ... etc. Of course, if one were certain that the spin of the emitting state were $3/2$, then a χ^2 analysis could be done, but this is a very unique situation. Figure 3-8 illustrates the measured distribution of the 0.35 MeV gamma ray. The least squares fit gives an A_2 coefficient smaller than the one from the correlation. This is due to the contributions from the $m = \pm 3/2$ and $m = \pm 5/2$ which have a tendency to make the correlation isotropic.

3.2 The 1.75 MeV Level

The assignment of a spin value for this level is aided by the fact that two gamma rays were observed; a 1.40 MeV gamma ray to the first excited state and a 1.75 MeV gamma ray to the ground state. The latter is extremely weak but nonetheless a correlation of sorts was extracted. The n-gamma correlations for these two gamma rays were measured with the neutron counter at zero degrees and the analysis follows the same lines as that of the 0.35 MeV gamma ray.

(a) The 1.4 MeV Gamma Ray

The correlation of the 1.40 MeV gamma ray was measured three separate times and the coefficients from the least squares fit of each correlation were averaged. The three measured correlations after all corrections except that for finite solid angle are shown in Figure 3-9. The average values of the coefficients corrected for solid angle are $A_2 = -.695 \pm .024$ and $A_4 = +.02 \pm .028$. From the analysis of the 0.35 MeV gamma ray it may now be assumed that the 1.40

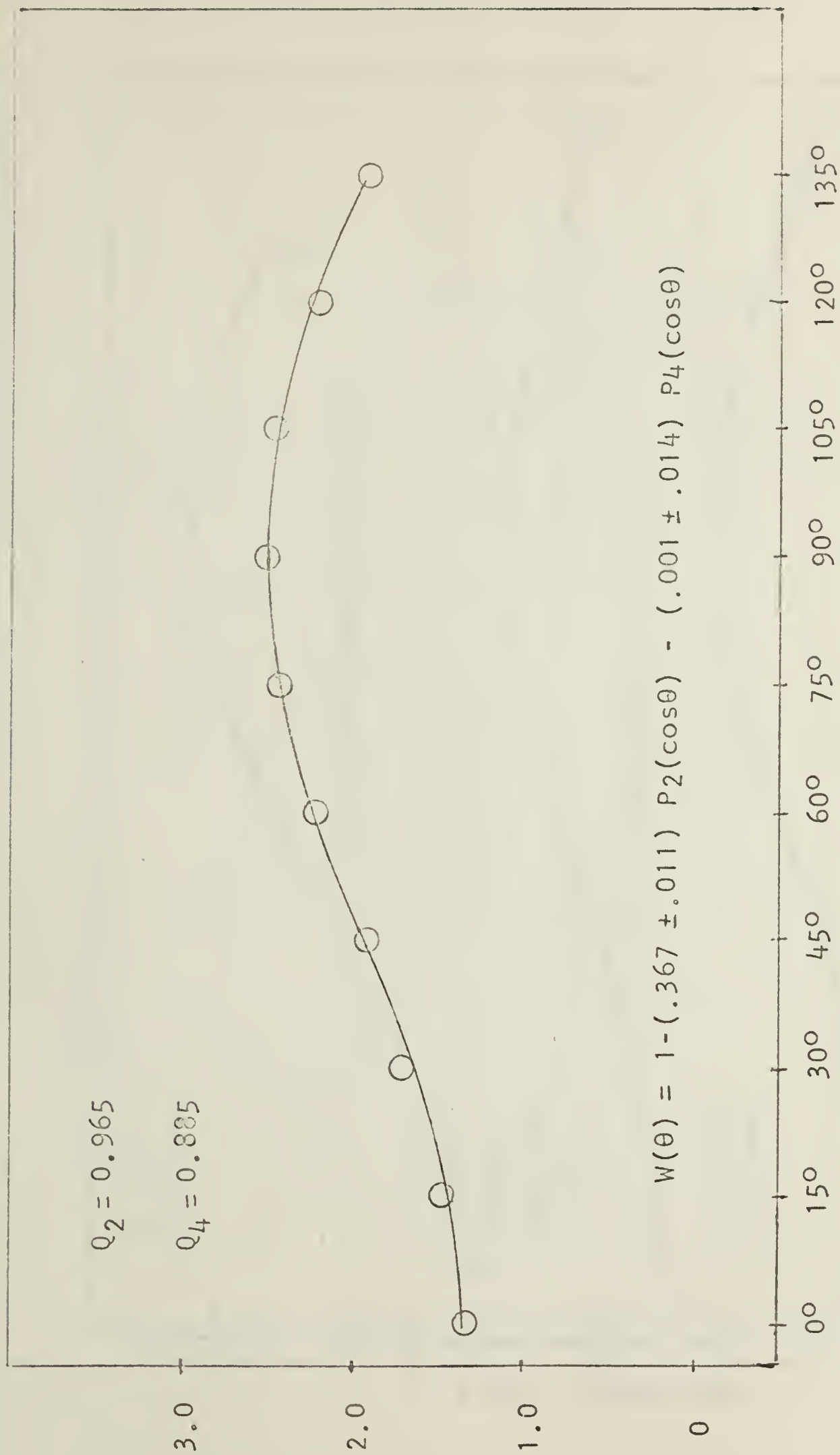


FIG. 3-8 THE DISTRIBUTION OF THE 0.35 MEV GAMMA RAY AT A BOMBARDING ENERGY OF 4.43 MEV.

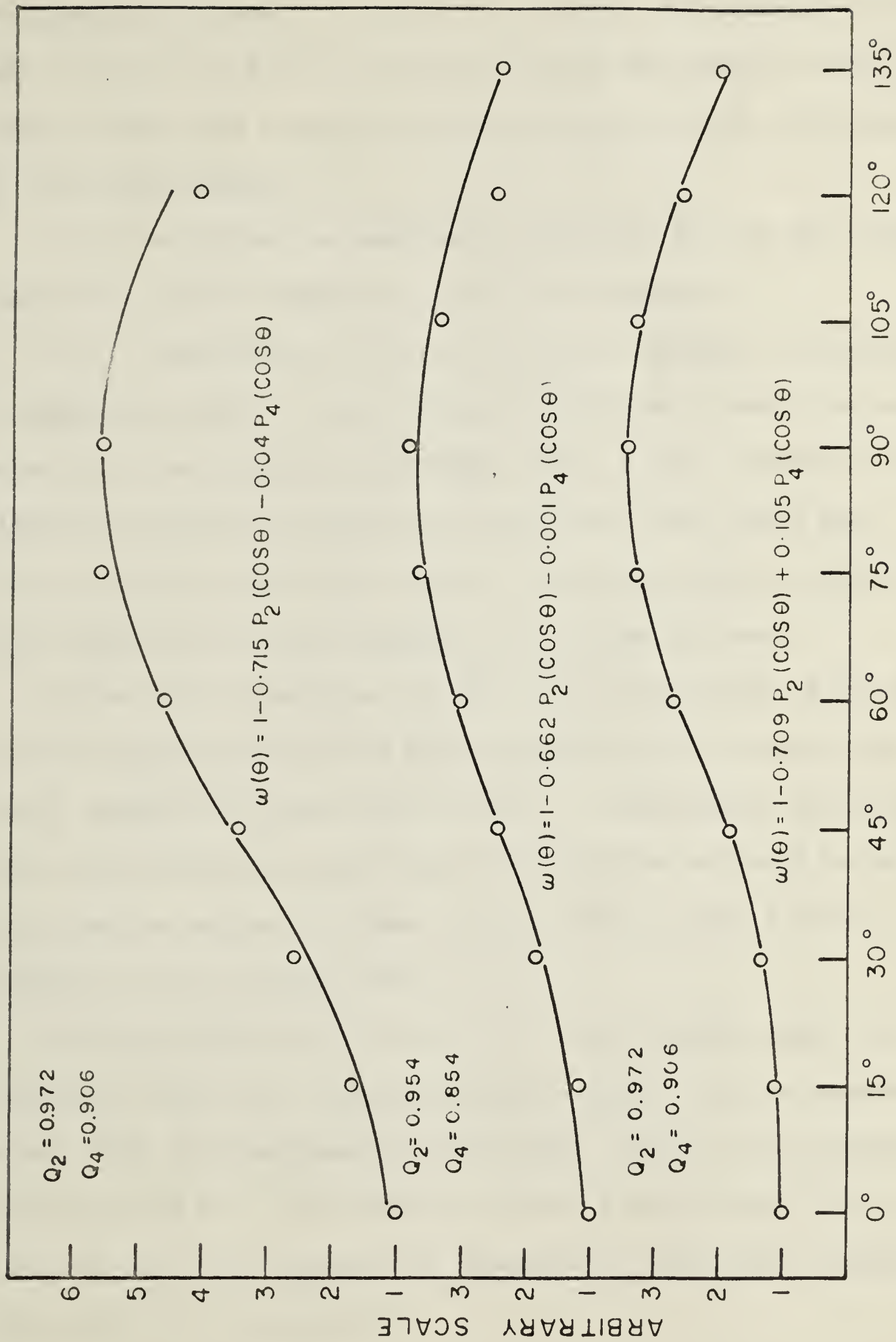


FIG. 3-9 THE MEASURED NEUTRON-GAMMA RAY CORRELATIONS OF THE 1.40 MEV GAMMA RAY AT A BOMBARDING ENERGY OF 4.43 MEV.

MeV gamma ray proceeds to a level of spin $5/2$. The assumption is also made that only $m = \pm 1/2$ is populated due to the geometry and $m = \pm 3/2$ substates make only a small contribution because of the solid angle of the neutron counter.

A spin of $1/2$ may be immediately eliminated because the correlation of the 1.40 MeV gamma ray is far from isotropic.

A spin combination of $3/2$ to $5/2$ does not generate a predicted A_2 coefficient which is large enough in magnitude to match the measured value. This is illustrated in Figure 3-10. A small contribution from $P(3/2)$ would make the predicted A_2 coefficient tend toward zero, farther from the experimental value. From this it can be concluded that a spin of $3/2$ is not possible for the 1.40 MeV level.

Figure 3-11 illustrates the fact that a spin change of $5/2$ to $5/2$ does not generate an A_2 value which agrees with the measured value. The A_4 coefficient agrees only for $\delta = 0$. A contribution of $P(3/2)$ makes the predicted A_2 coefficient less negative and would not help in gaining an agreement between the two. Thus a spin of $5/2$ is excluded for the 1.75 MeV level.

A spin combination of $7/2$ to $5/2$ for the 1.40 MeV gamma ray generates a predicted correlation which overlaps with the measured value. This is illustrated in Figure 3-12. There is good agreement in both A_2 and A_4 . It is possible to have a contribution from $m = \pm 3/2$ substates and still maintain the agreement as illustrated in Figure 3-14. This gives $\delta = + 0.19 \pm 0.02$.

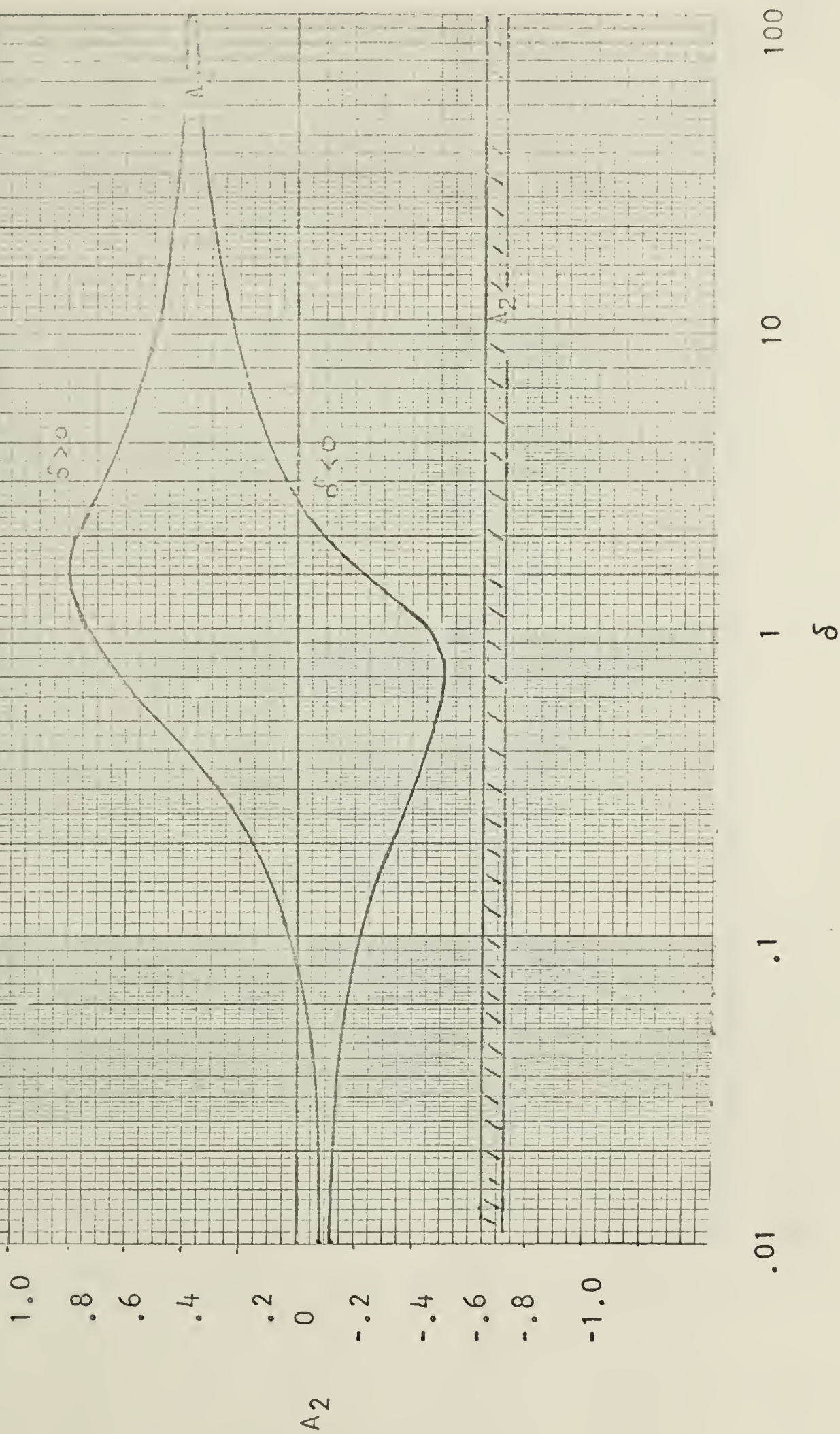


FIG. 3-10 A PLOT OF A_2 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $3/2$ TO $5/2$. THE SHADED BAR IS THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 COEFFICIENT FOR THE 1.40 MEV GAMMA RAY. THE A_4 IS PREDICTED TO BE ZERO.

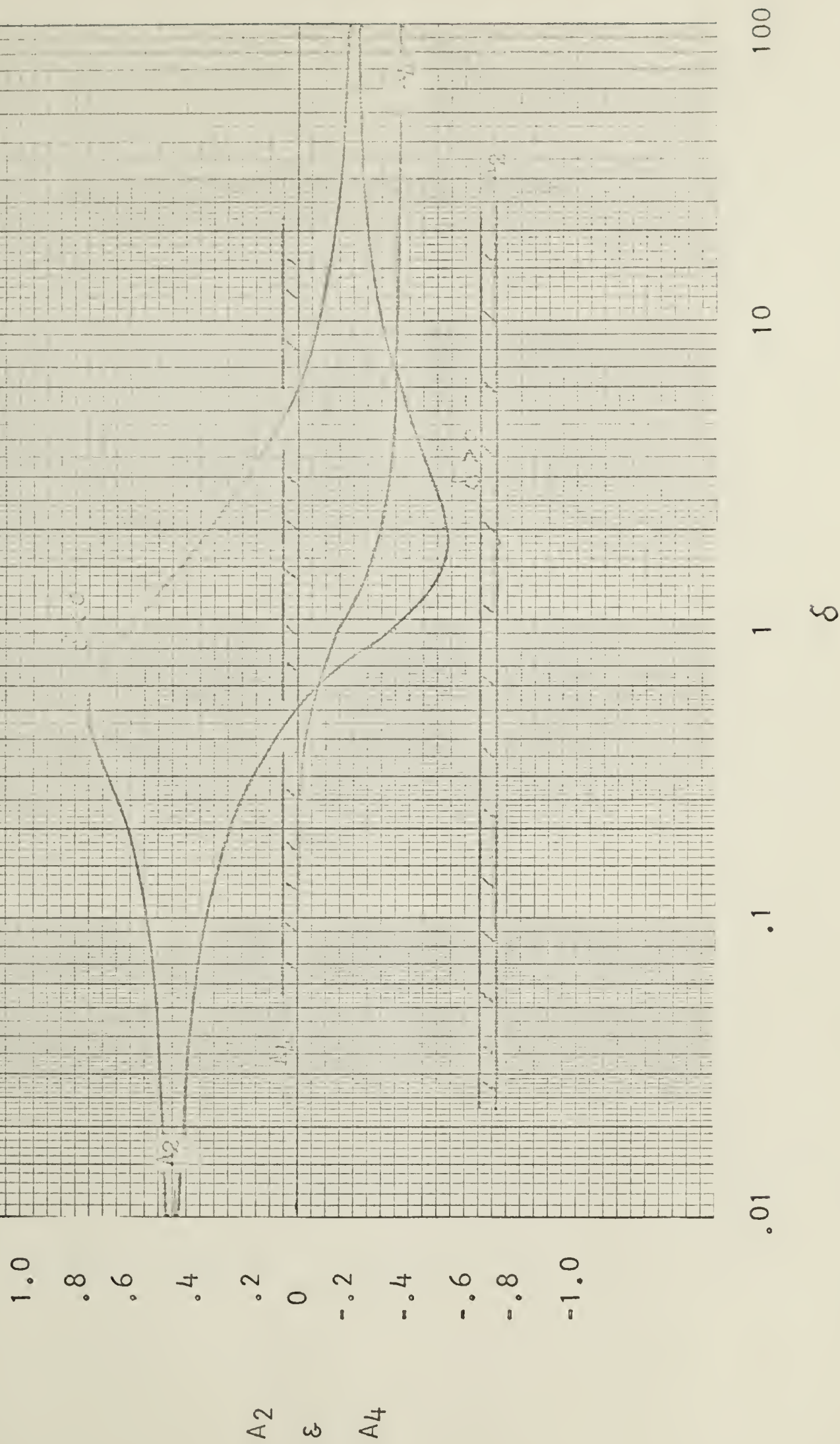


FIG. 3-11 A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $5/2$ TO $5/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.40 MEV GAMMA RAY.

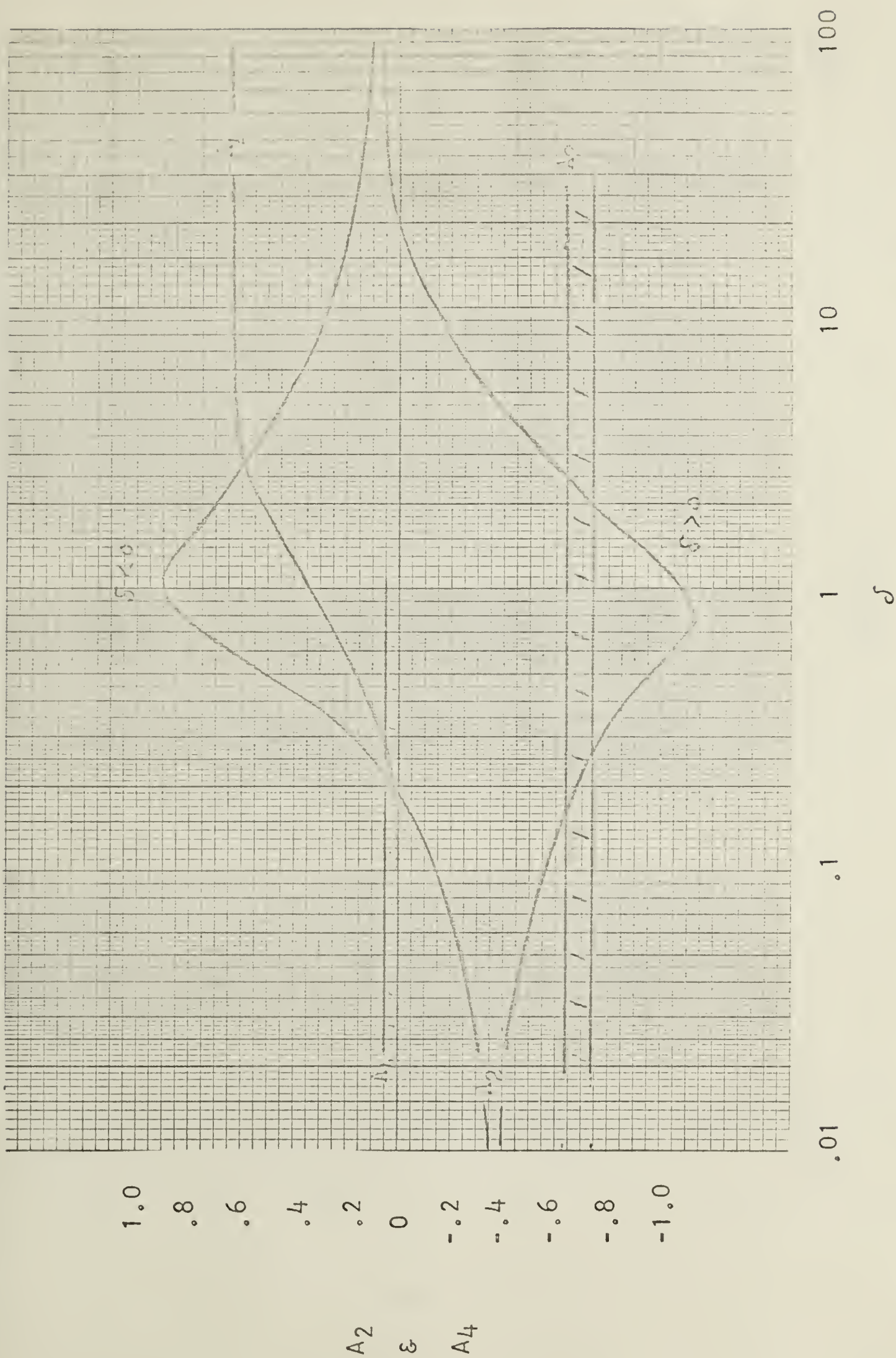


FIG. 3-12 A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $7/2$ TO $5/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.40 MEV GAMMA RAY.

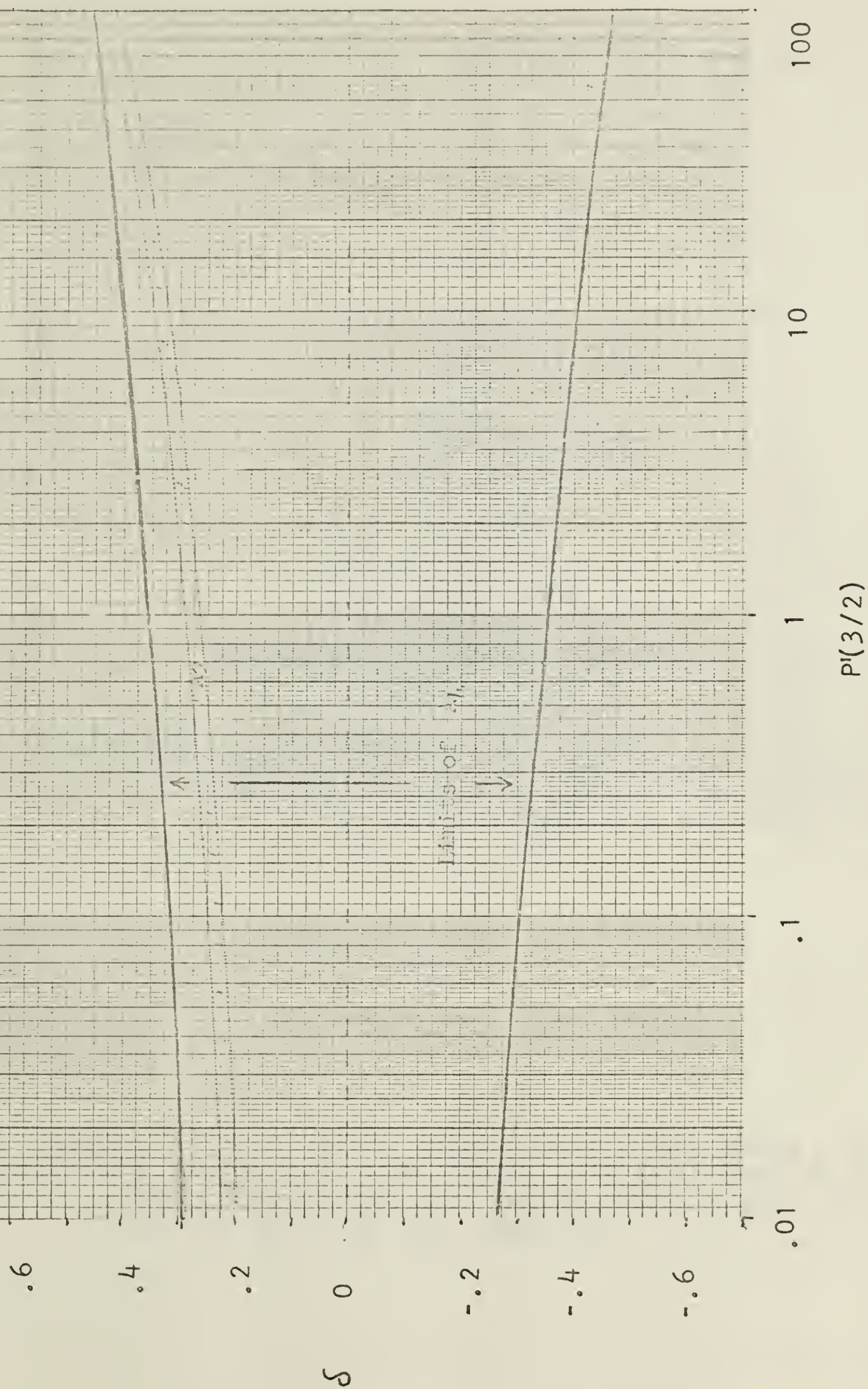


FIG. 3-13 A PLOT OF δ VERSUS $P'(3/2)$ USING THE MEASURED VALUES OF A_2 AND A_4 FOR THE 1.40 MEV GAMMA RAY AND THE PREDICTED COEFFICIENTS FOR A $7/2$ TO $5/2$ SPIN CHANGE.

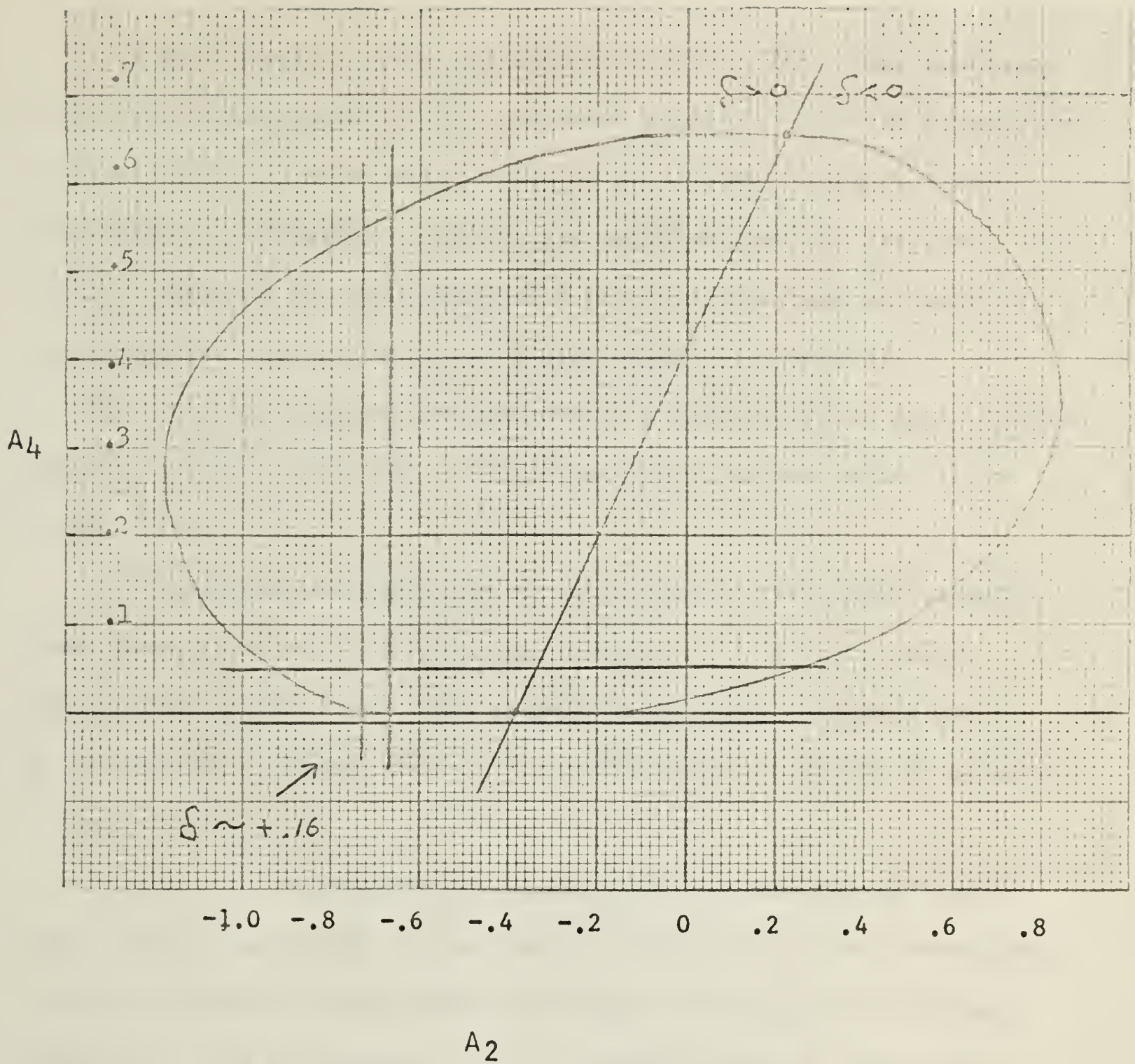


FIG. 3-14 A PLOT OF A_2 VERSUS A_4 FOR ALL VALUES OF δ FOR A $7/2$ TO $5/2$ SPIN CHANGE, ASSUMING ONLY $P(1/2)$. THE CROSSED BARS ARE THE MEASURED VALUES OF A_2 AND A_4 FOR THE 1.40 MEV GAMMA RAY.

The last possible spin combination is $9/2$ to $5/2$. This generates an A_2 coefficient which is far from being negative enough as illustrated by Figure 3-15. Even a contribution of $P(3/2)$ would tend to make the predicted A_2 coefficient slightly less negative than for the pure $P(1/2)$. There is an overlapping with the A_4 coefficient but this is not enough positive evidence for a spin change of $9/2$ to $5/2$.

The analysis thus far indicates that a spin of $7/2$ is most probable for the 1.75 MeV level with a dipole-quadrupole mixing ratio of $\delta = + 0.19 \pm 0.02$.

A χ^2 analysis was performed on the average of the three correlations shown in Figure 3-9 for a spin change of $7/2$ to $5/2$. This assumes that $P(1/2)$ is the only non-zero population parameter and is illustrated in Figure 3-16. This indicates the best fit to be with a δ of $+ 0.176$.

Figure 3-17 illustrates the distribution of the 1.40 MeV gamma ray. The A_2 coefficient is less negative than that of the correlation. This is an indication that substates other than $m = \pm 1/2$ are being populated. This distribution has no immediate value by itself but when combined with the distribution of the 1.75 MeV gamma ray, yields very useful information. This is shown in part D of this Section.

(b) The 1.75 MeV Gamma Ray

Only one distribution and one correlation were measured for this gamma ray because of the low counting rate. This was done at 4.43 MeV bombarding energy. The standard deviations are extremely large compared

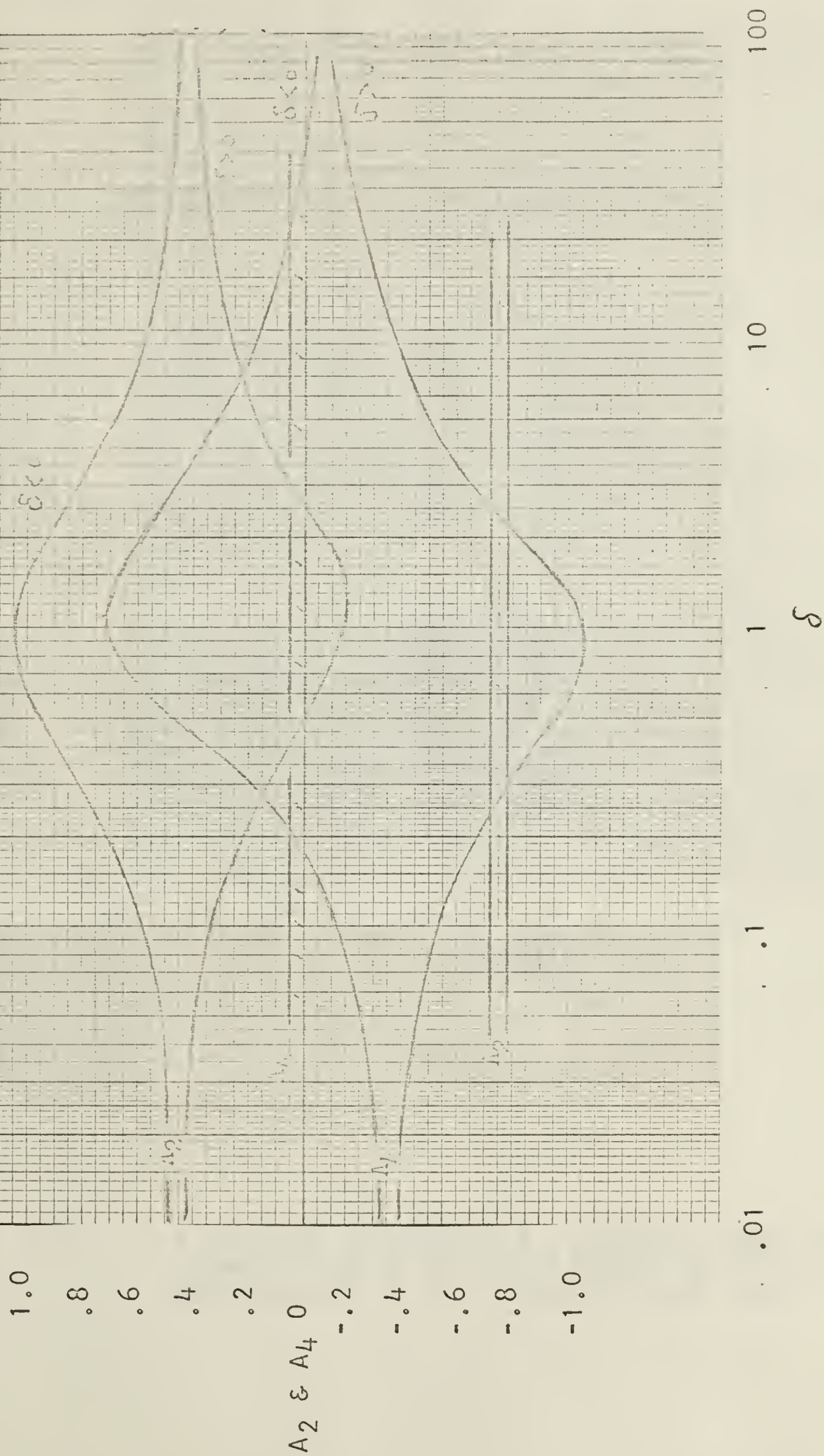


FIG. 3-15

A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $9/2$ TO $5/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.40 MEV GAMMA RAY.

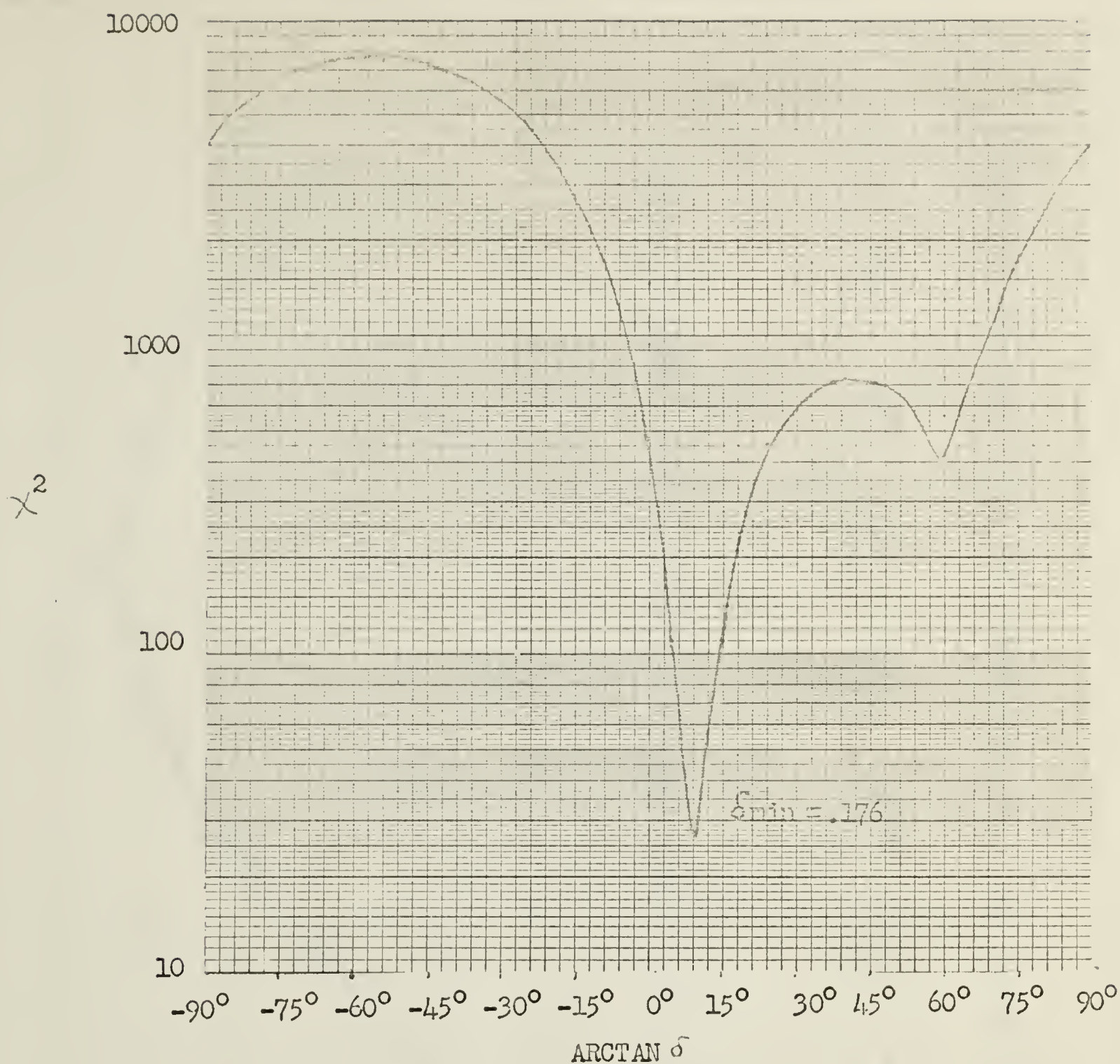


FIG. 3-16

2

A PLOT OF χ^2 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ AND USING A 7/2 TO 5/2 SPIN CHANGE WITH THE N-GAMMA CORRELATION OF THE 1.40 MEV GAMMA RAY.

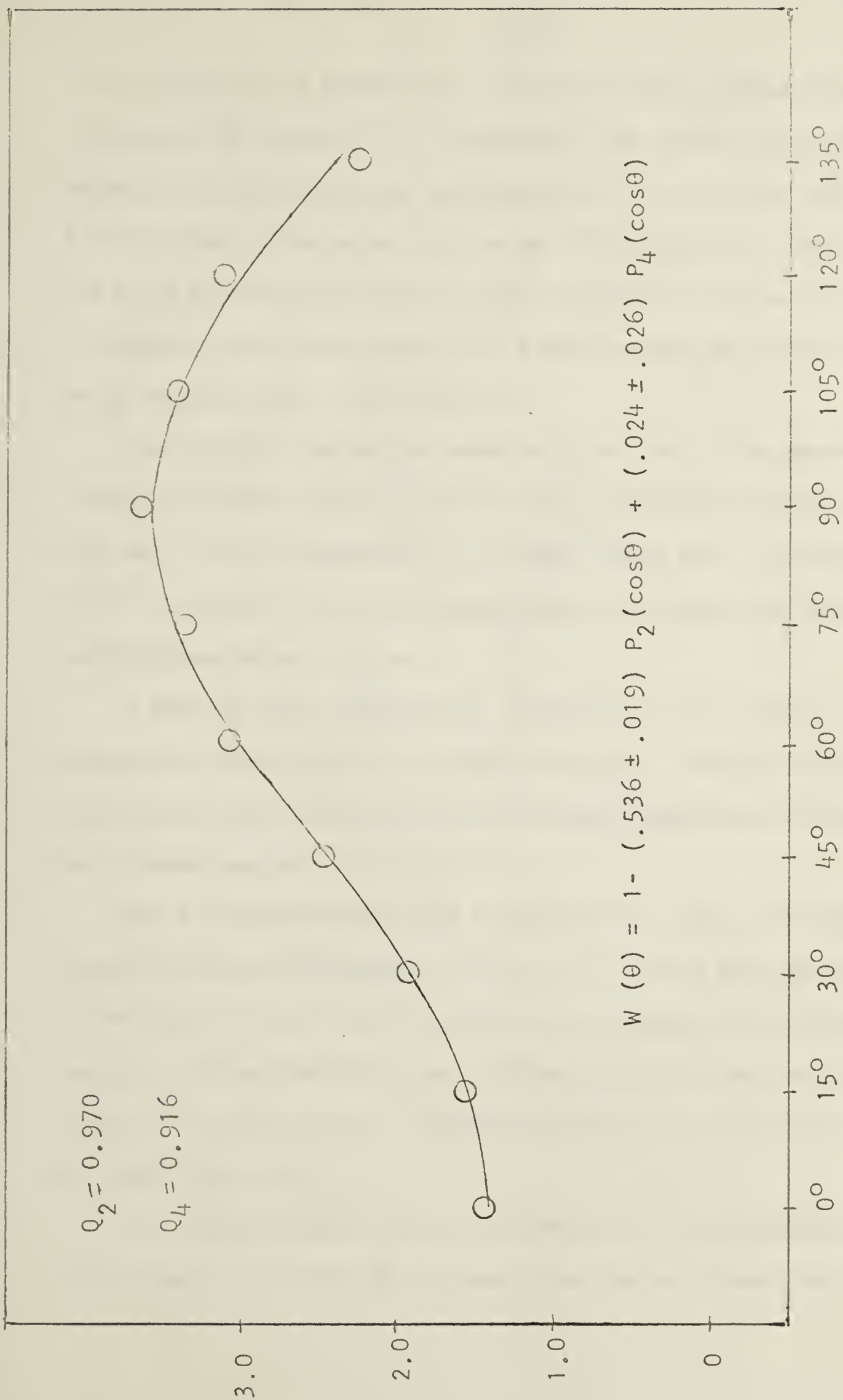


FIG. 3-17 THE DISTRIBUTION OF THE 1.40 MEV GAMMA RAY AT A BOMBARDING ENERGY OF 4.43 MEV.

to the previous two gamma rays. The distribution and correlation are illustrated in Figure 3-18. Nonetheless, the coefficients have useable values which help in giving an unambiguous value for the spin of the 1.75 MeV level. The value of δ falls within very wide limits due to the large standard deviations on the coefficients and to the fact that no correction has been applied for a small amount of pulse pile up which certainly must have occurred.

The distribution has no immediate value due to the number of unknown parameters but the correlation has been interpreted in the same way as the correlations of the other gamma rays. Assuming $P(1/2)$ to be the only non-zero population parameter, the various spin combinations can be analyzed.

A spin of $1/2$ is immediately ruled out for the correlation is substantial enough not to be called isotropic. The fact that the distribution also has statistically non-zero coefficients supports the argument against a spin of $1/2$.

For a transition where the initial state is $3/2$, the highest Legendre polynomial possible is $P_2(\cos \theta)$. In the case of the measured correlation of the 1.75 MeV level, the coefficient of the $P_4(\cos \theta)$ term, A_4 , is far from being zero. This indicates that the 1.75 MeV level is not $3/2$ in spin. This spin value is not supported by the 1.40 MeV gamma ray either.

For a spin change of $5/2$ to $3/2$ there is an overlapping of the A_2 coefficient but not for the A_4 coefficient as is illustrated in Figure 3-19.

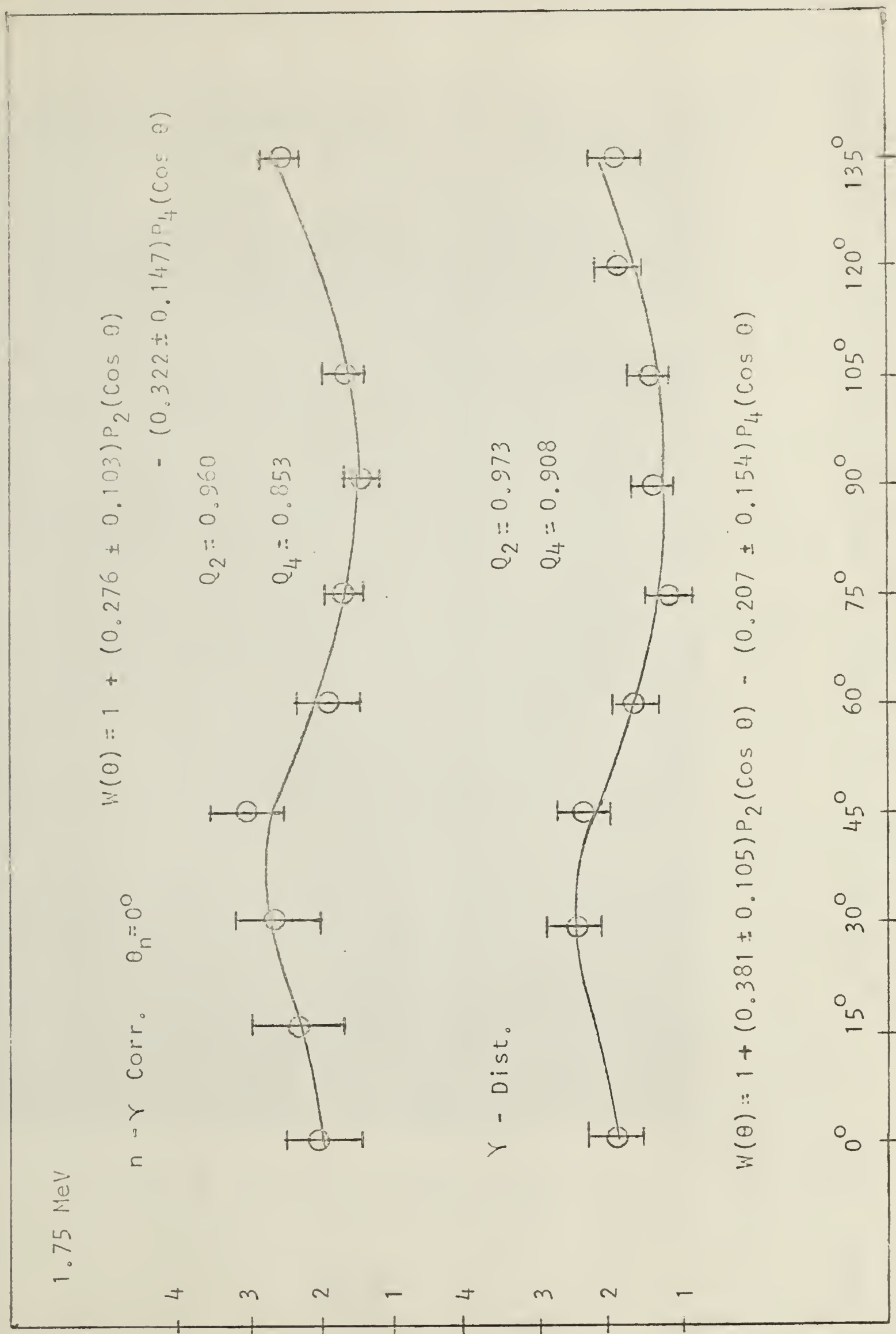


FIG. 3-18 THE N - GAMMA CORRELATION AND DISTRIBUTION OF THE 1.75 MEV GAMMA RAY.

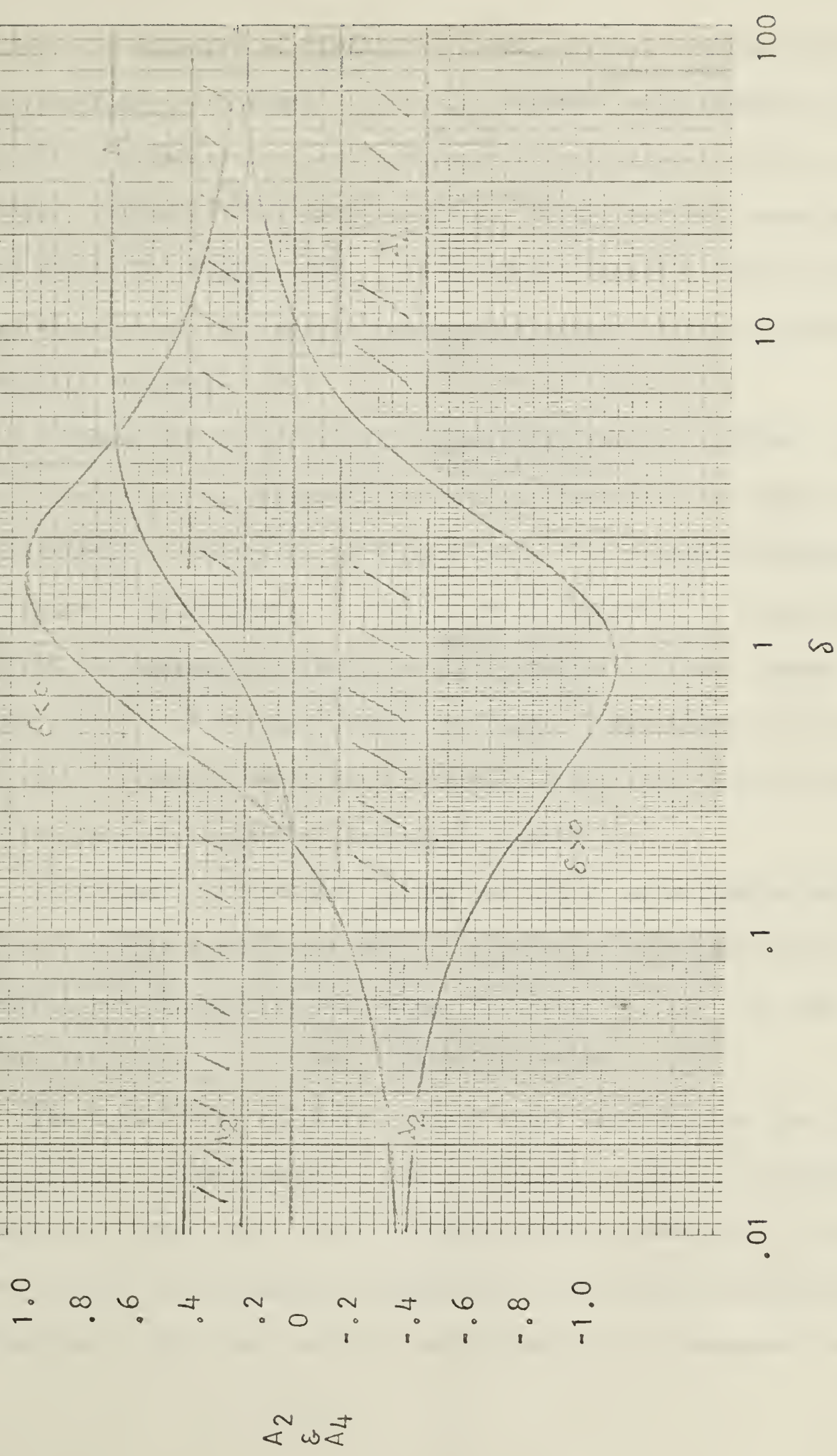


FIG. 3-19

A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $5/2$ TO $3/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.75 MEV GAMMA RAY.

In fact the measured A_4 coefficient does not have the same sign as the predicted coefficient. There is, however, an agreement reached for both coefficients if one considers a very large contribution of $P(3/2)$. Figure 3-20 illustrates this. This agreement comes about with a $P(3/2)$ of about 70%. One would not expect a $P(3/2)$ contribution as great as this due to the geometry favoring the population of $m = \pm 1/2$ substates.

A transition of $7/2$ to $3/2$ is suitable for the 1.75 MeV gamma ray. There is good agreement between the predicted and measured coefficients as indicated by Figure 3-21. The agreement remains with small contributions of $P'(3/2)$ as is indicated by Figure 3-22, in fact the agreement is best for $.15 \leq P'(3/2) \leq 2.0$. Figure 3-23 shows that a δ of +7 is a better fit than a lower value of $\delta = +.03$. A δ of +7 is unreasonable for a mixture of $E2/M3$ or $M2/E3$ and the $\delta = +.03$ is more reasonable although a poorer fit.

An χ^2 analysis assuming $P(1/2)$ and $P(3/2)$ as variables was performed for this correlation and is illustrated in Figure 3-24. This also has two minima with the better fit being for a $\delta = +7$ and the poorer fit being for a δ of +.0315 and $P'(3/2) = .383$.

The possibility of there being a small contribution from summing of 0.35 and 1.40 MeV gammas in the 1.75 MeV correlation and distribution is not ruled out. If at the time of the correlation, a check were made as to the amount of summing at a particular angle, then a normalized correlation could be subtracted from the measured correlation.

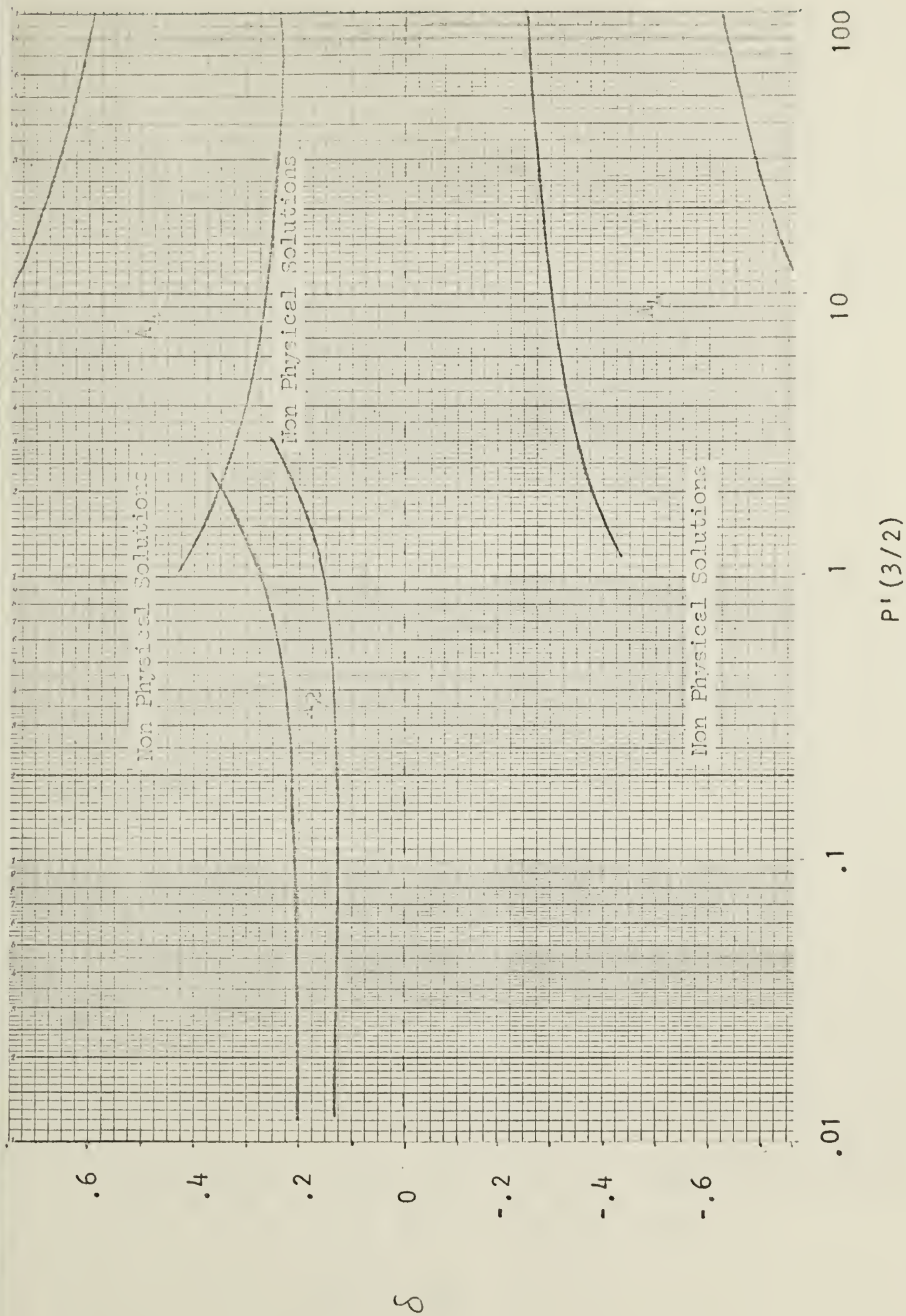


FIG. 3-20 A PLOT OF δ VERSUS $P'(3/2)$ USING THE MEASURED VALUES OF A_2 AND A_4 FOR THE 1.75 MEV GAMMA RAY AND THE PREDICTED COEFFICIENTS FOR A $5/2$ TO $3/2$ SPIN CHANGE.

A_2
 ϵ
 A_4

1.0
 .8
 .6
 .4
 .2
 0
 -.2
 -.4
 -.6
 -.8
 -1.0

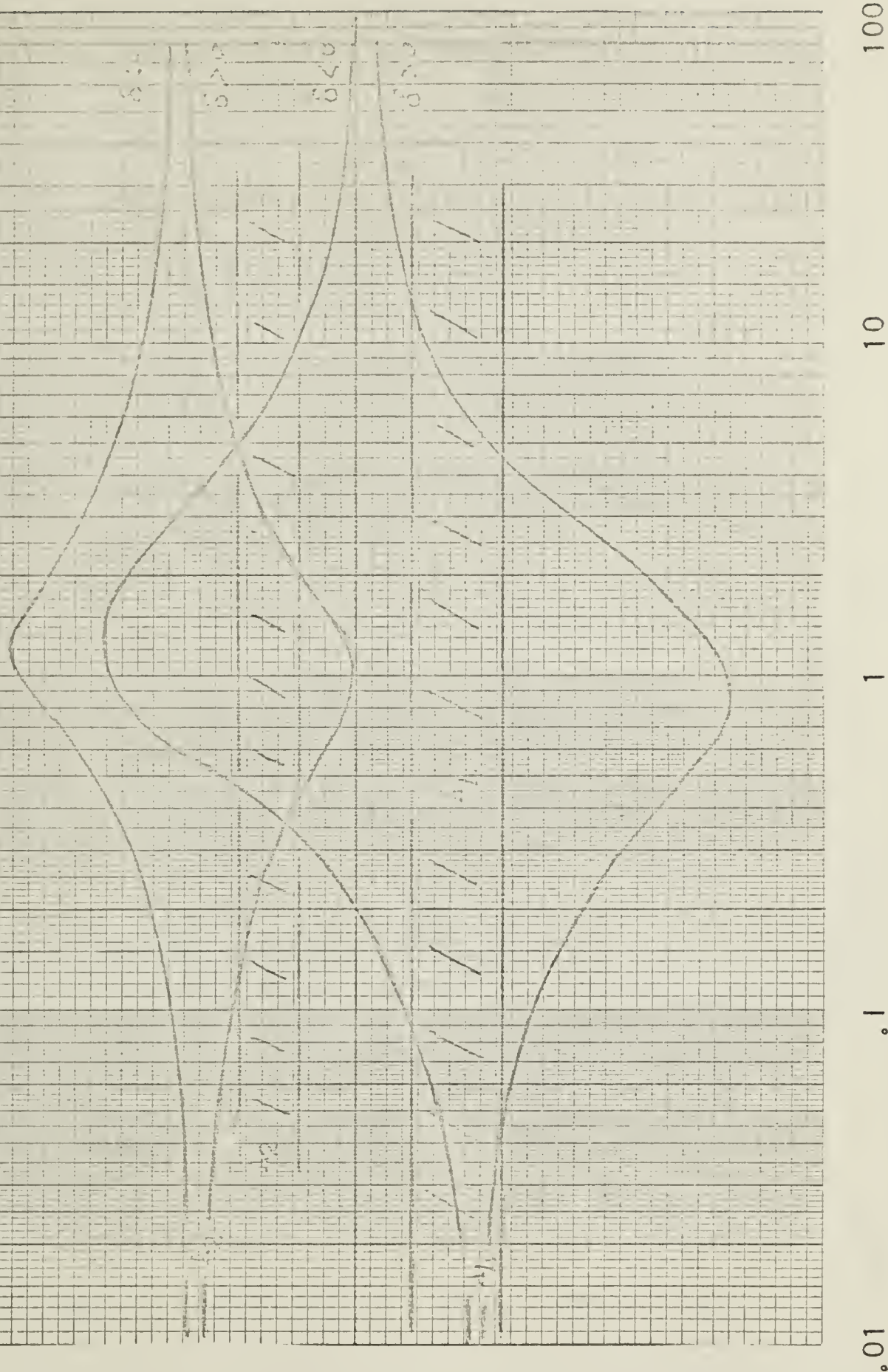


FIG. 3-21

A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $7/2$ TO $3/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.75 MEV GAMMA RAY.

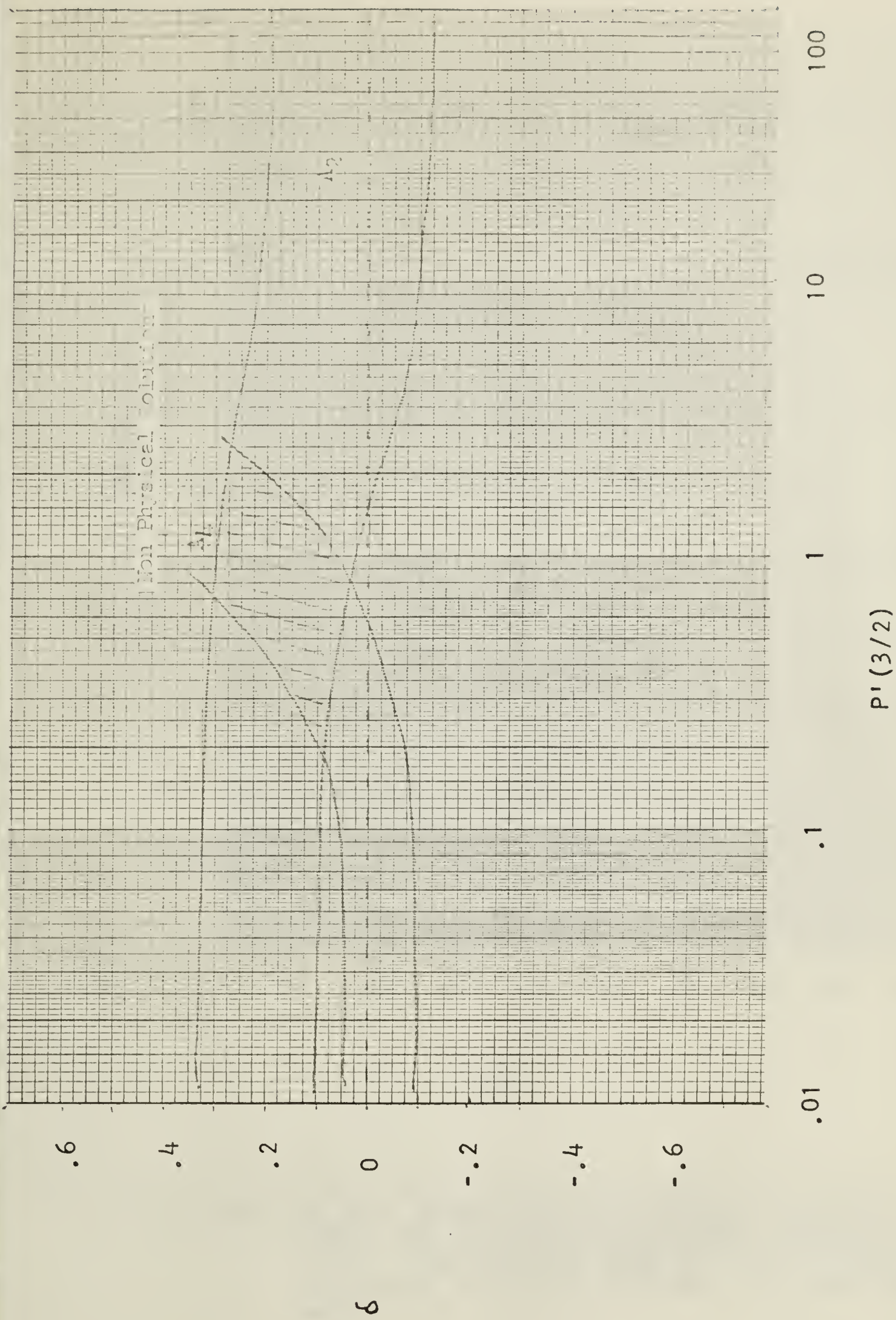


FIG. 3-22 A PLOT OF δ VERSUS $P'(1/2)$ USING THE MEASURED VALUES OF A_2 AND A_4 FOR THE 1.75 MEV GAMMA RAY AND THE PREDICTED COEFFICIENTS FOR A $7/2$ TO $3/2$ SPIN CHANGE.

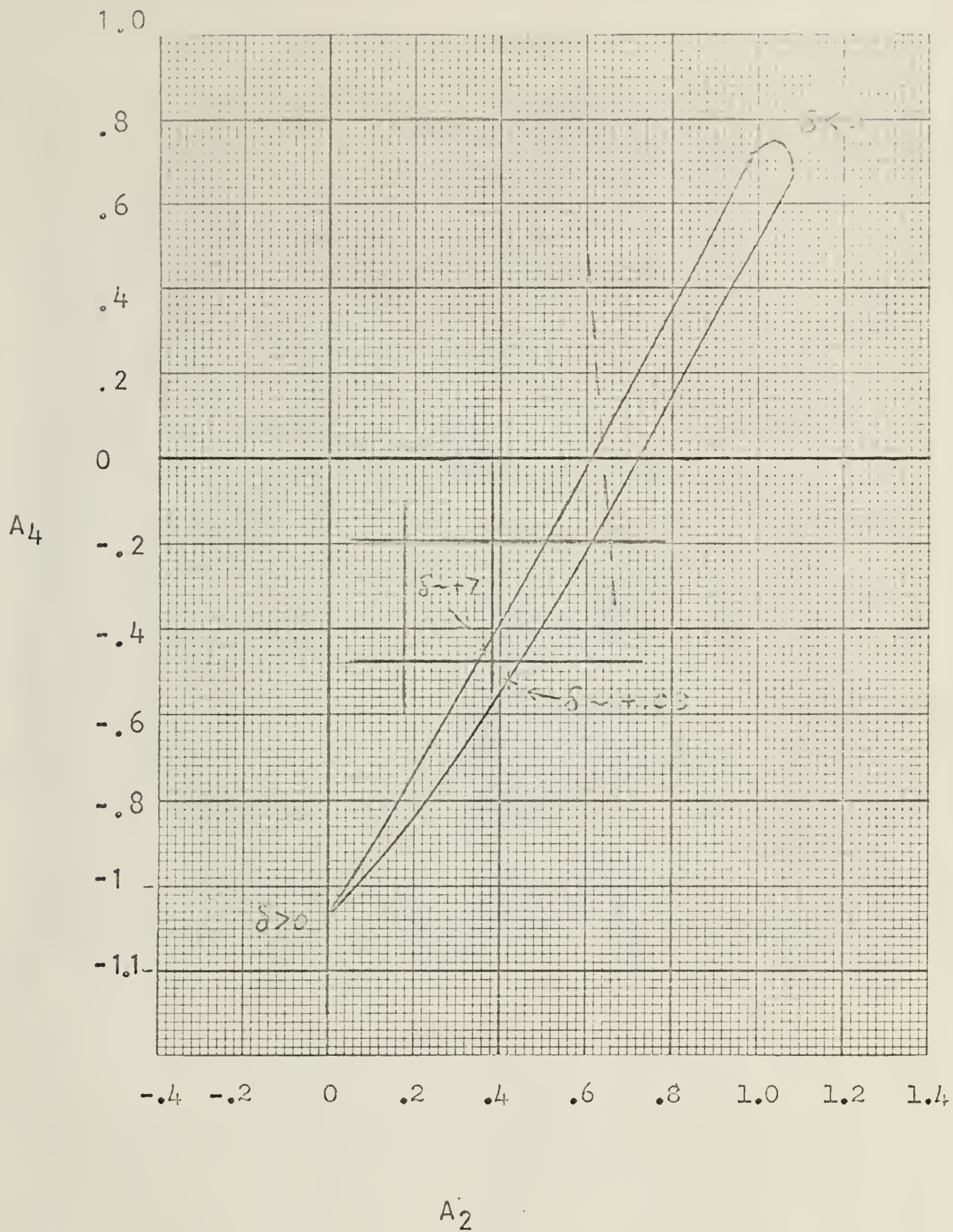


FIG. 3-23 A PLOT OF A_2 VERSUS A_4 FOR ALL VALUES OF δ FOR A $7/2$ TO $3/2$ SPIN CHANGE, ASSUMING ONLY $P(\frac{1}{2})$. THE CROSSED BARS ARE THE MEASURED VALUES OF A_2 AND A_4 FOR THE 1.75 MEV GAMMA RAY.

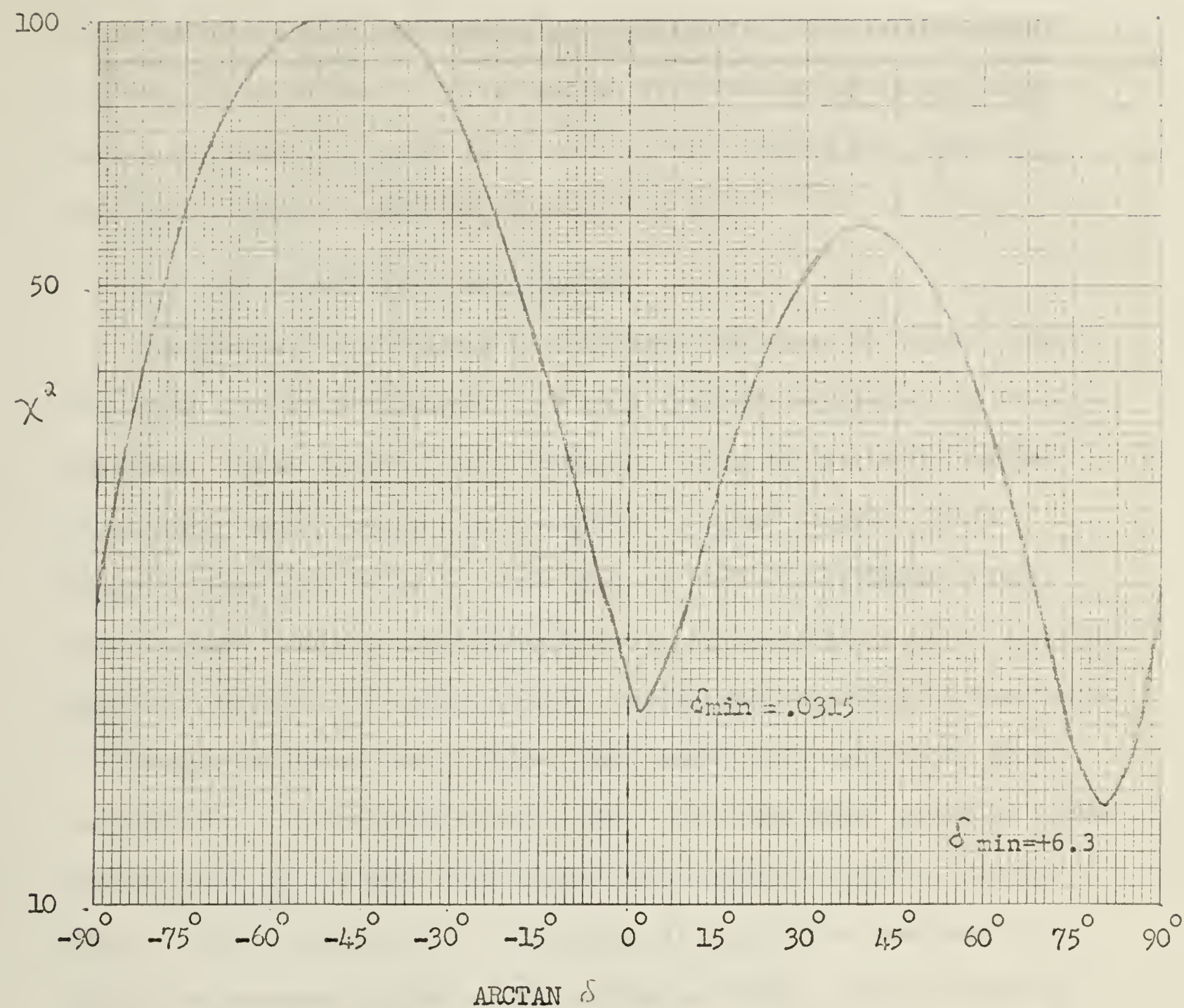


FIG. 3-24

A PLOT OF χ^2 VERSUS δ , ASSUMING $P(1/2)$ AND $P(3/2)$ FOR A SPIN CHANGE OF $7/2$ TO $3/2$ WITH THE 1.75 MEV GAMMA RAY CORRELATION. AT THE MINIMUM VALUE OF χ^2 , $P(3/2)/P(1/2) = .382$ AND $\delta_{\min} = .0315$.

There was no summing measurement made during the correlation so no correction can be made. It is assumed that the add up is not large enough to change the measured mean value of δ beyond the limits of the large standard deviation accompanying it.

(c) The Gamma-Gamma Correlations

The measured gamma-gamma correlations are shown in Figure 3-25. The major problem encountered with this type of correlation is in the analysis. Smith (Sm 64a) has developed a very sophisticated method of analysis which requires an elaborate computer program. This method was not available for this work so that any reliable information to come from the correlations would require the use of a laborious graphical method. Of course, major simplifications would be introduced if the initial level were $1/2$ for then there would only be δ_1 and δ_2 as unknowns. If the initial level were $3/2$, then there would be three unknowns and if the spin were higher, the unknowns would be far too many to handle graphically. Of course, if there were some way to limit the non-zero population parameters to $P(1/2)$, the job would be easier. This would require a neutron counter at zero degrees and triple coincidence analysis, reducing the counting rate below an acceptable level.

Because of the difficulties in analyzing the data, only one spin combination has been tried, that is the values that the n-gamma ray correlations have shown to be most reasonable, namely $7/2$ to $5/2$ to $3/2$. The goal is then to find values of δ for the 0.35 MeV and 1.40 MeV gamma

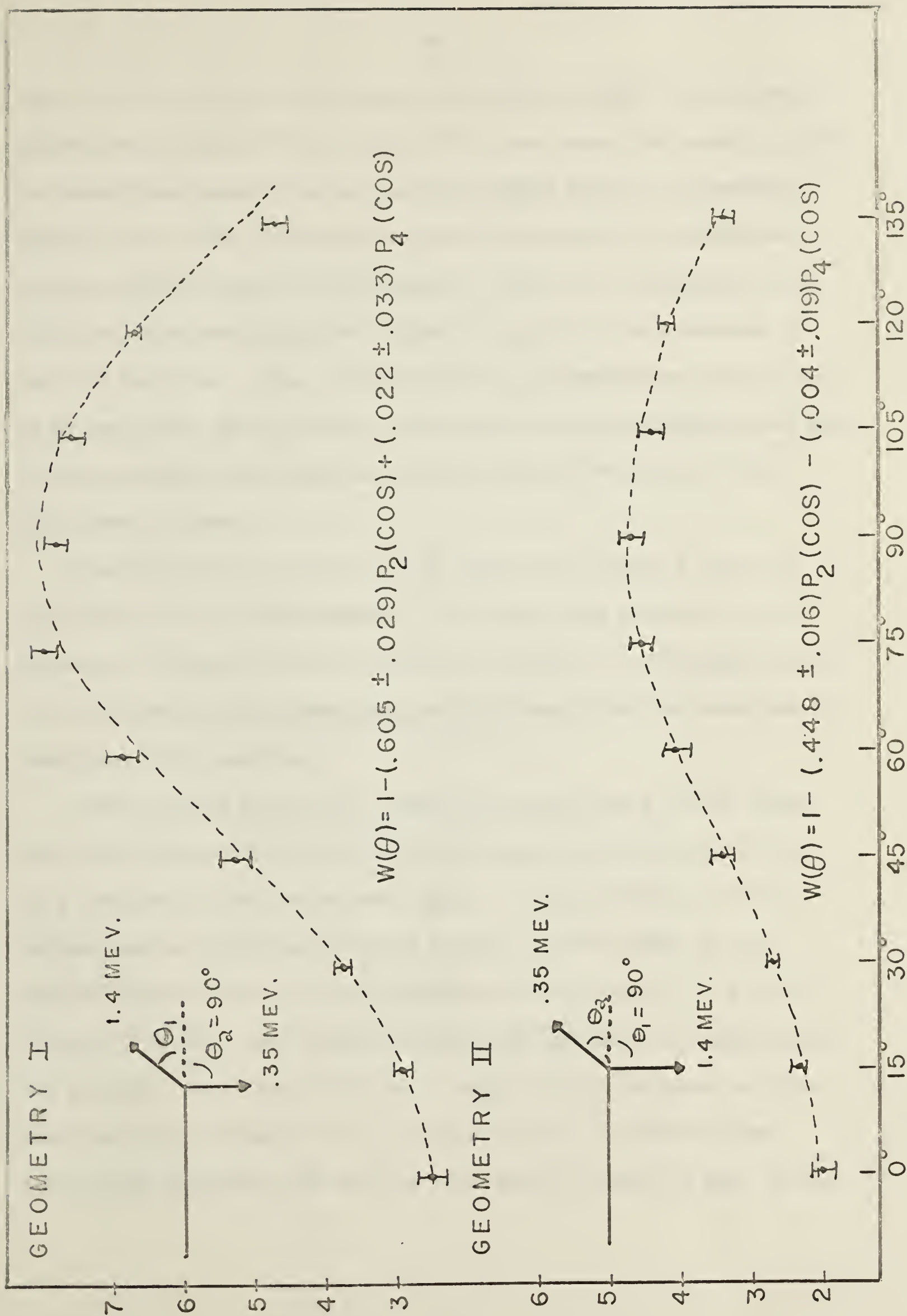


FIG. 3-25 THE GAMMA-GAMMA CORRELATIONS.

rays. In order to do this properly the unknown normalized population parameters, $P'(3/2)$, $P'(5/2)$, and $P'(7/2)$ are needed for there are only two gamma-gamma geometries and they are needed for the two unknown mixing ratios. The difference in the distribution and correlation of the 1.40 MeV gamma ray has shown that there is a substantial contribution from populations other than $m = \pm 1/2$ in the formation of the 1.75 MeV level. Thus if only the $m = \pm 1/2$ substates were assumed to be populated, then δ_1 and δ_2 found would be an approximation at best. The approximation would improve progressively as $P'(3/2)$, $P'(5/2)$, etc., were included.

The distribution of the 1.75 MeV gamma ray affords a means of evaluating some of these unknowns. Of course, the population parameters are the same for the distribution of the 1.75 MeV gamma ray as those involved in the gamma-gamma correlations, since the experimental conditions were identical.

There are two measureable coefficients from the 1.75 MeV gamma ray distribution. This is actually not enough for each coefficient is a function of four parameters, $A_k[\delta, P'(3/2), P'(5/2), P'(7/2)]$. One may now go to the distribution of the 1.40 MeV gamma ray for another equation, but its coefficients are functions of δ_1 , $P'(3/2)$, $P'(5/2)$, $P'(7/2)$. This would introduce the unknown, δ_1 , complicating the process. Even though this is a total of five unknowns and five measureable coefficients it is a formidable job to handle. Some simplifying approximations must be introduced in order to make the job

practical. First of all the value of +0.03 for δ_3 found in the n-gamma correlation of the 1.75 MeV gamma ray is an extremely good value to use since a value close to zero is expected for an octupole/quadrupole ratio and any value much less than 0.1 does not effect the correlation very strongly. The other assumption is that $P'(7/2)$ is identically zero. This may not be strictly true, but it is the smallest of all the population parameters, for the smaller neutron angular momenta are favoured. With these two assumptions, $P'(3/2)$ and $P'(5/2)$ can be approximated from the distribution of the 1.75 MeV gamma ray.

With the assumptions mentioned the A_2 and A_4 coefficients reduce from those given in Appendix A to:

$$A_2 = \frac{[.467 + .285 P'(3/2) - .095 P'(5/2)]}{[1 + P'(3/2) + P'(5/2)]}$$

$$A_4 = \frac{-.425 + .141 P'(3/2) + .615 P'(5/2)}{[1 + P'(3/2) + P'(5/2)]}$$

The measured coefficients are $A_2 = + 0.381 \pm 0.105$ and $A_4 = -0.207 \pm 0.154$. Equating the measured to the predicted coefficient over the range of each coefficient determined by their standard deviations results in the plot of Figure 3-26. From this graph it can be seen that the least squares values of A_2 and A_4 result in the intersection of two straight lines in the positive quadrant. This quadrant is the only meaningful one since

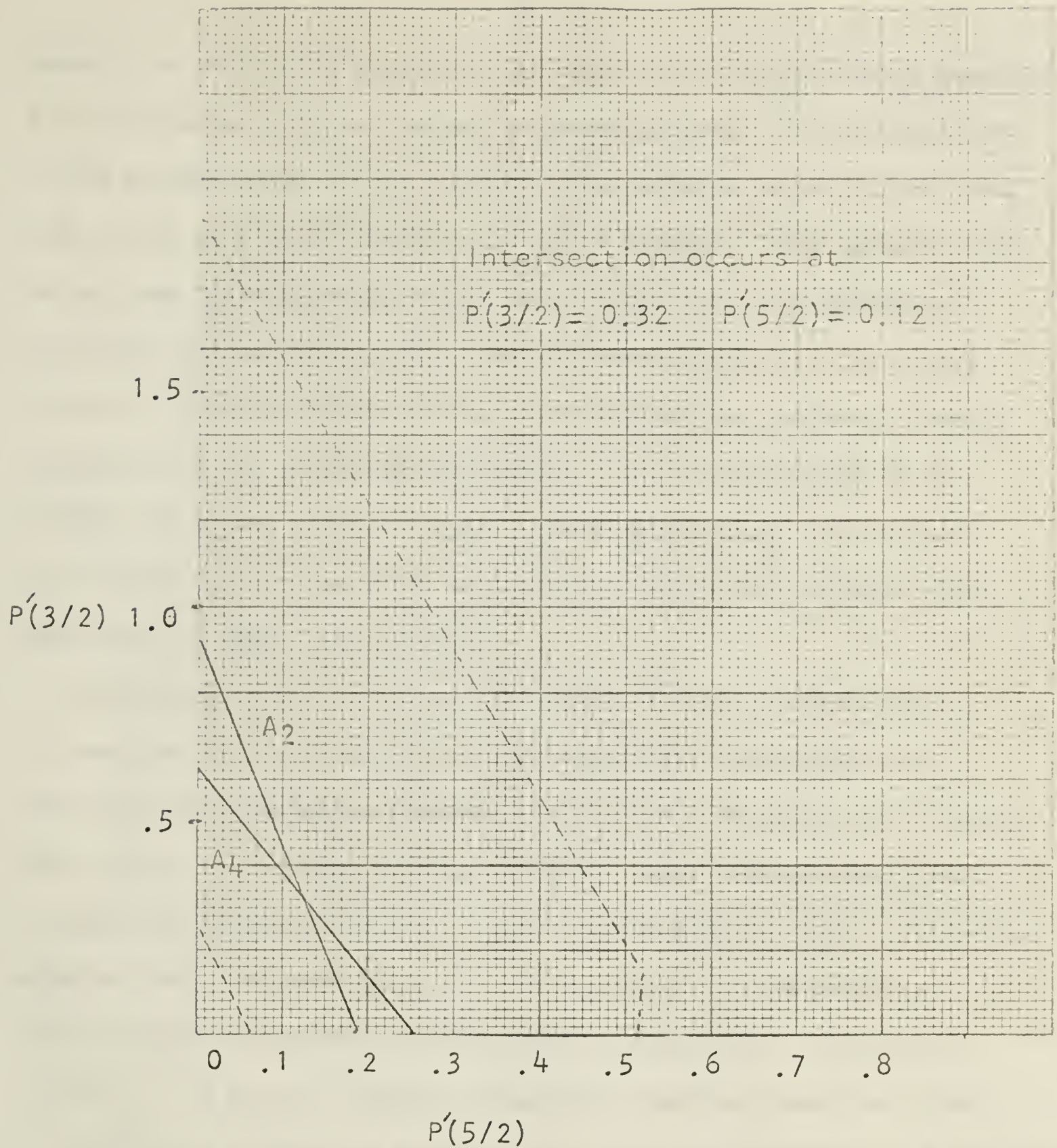


Fig. 3-26

A PLOT OF $P'(3/2)$ VERSUS $P'(5/2)$ TAKEN FROM THE DISTRIBUTION OF THE 1.75 MeV GAMMA RAY. THE DASHED LINES INDICATE THE AREA IN WHICH THE POPULATION PARAMETERS MUST LIE.

negative values of the population parameters are not physically possible. For this reason, this is the only quadrant plotted. If the values of A_2 and A_4 determined by the limits of the standard deviation are used, then limits on $P'(3/2)$ and $P'(5/2)$ can be imposed. This results in the dashed area illustrated in Figure 3-26 in which the two normalized population parameters must lie. It is reasonable to use the intersection of the mean values as the point determining the most probable values of the two population parameters. This intersection is at $P'(3/2) = 0.32$ and $P'(5/2) = 0.12$. These calculations are limited by the fact that the standard deviations of these two parameters are large and not taken into account.

Referring to the equations of Appendix B where the predicted correlations for a $7/2$ to $5/2$ to $3/2$ cascade are listed, one may substitute the population parameters $P'(3/2) = 0.32$ and $P'(5/2) = 0.12$. This reduces the coefficients to a simpler form. The measured values of these coefficients are $B_2^I = -.605 \pm .029$ and $B_2^{II} = -.448 \pm .016$. By equating these measured values to the equations for the predicted correlations, two equations result which are quadratic functions of δ_1 and δ_2 . If a plot is made of these two equations using the limits of the B_k^i 's, a solution is found to lie in an area indicated in Figure 3-27. The center of this area is $\delta_1 = + 0.18$ and $\delta_2 = + 0.08$. This is an exact graphic solution of the gamma-gamma correlation equation, the only error being introduced by the inexact knowledge of the population parameters.

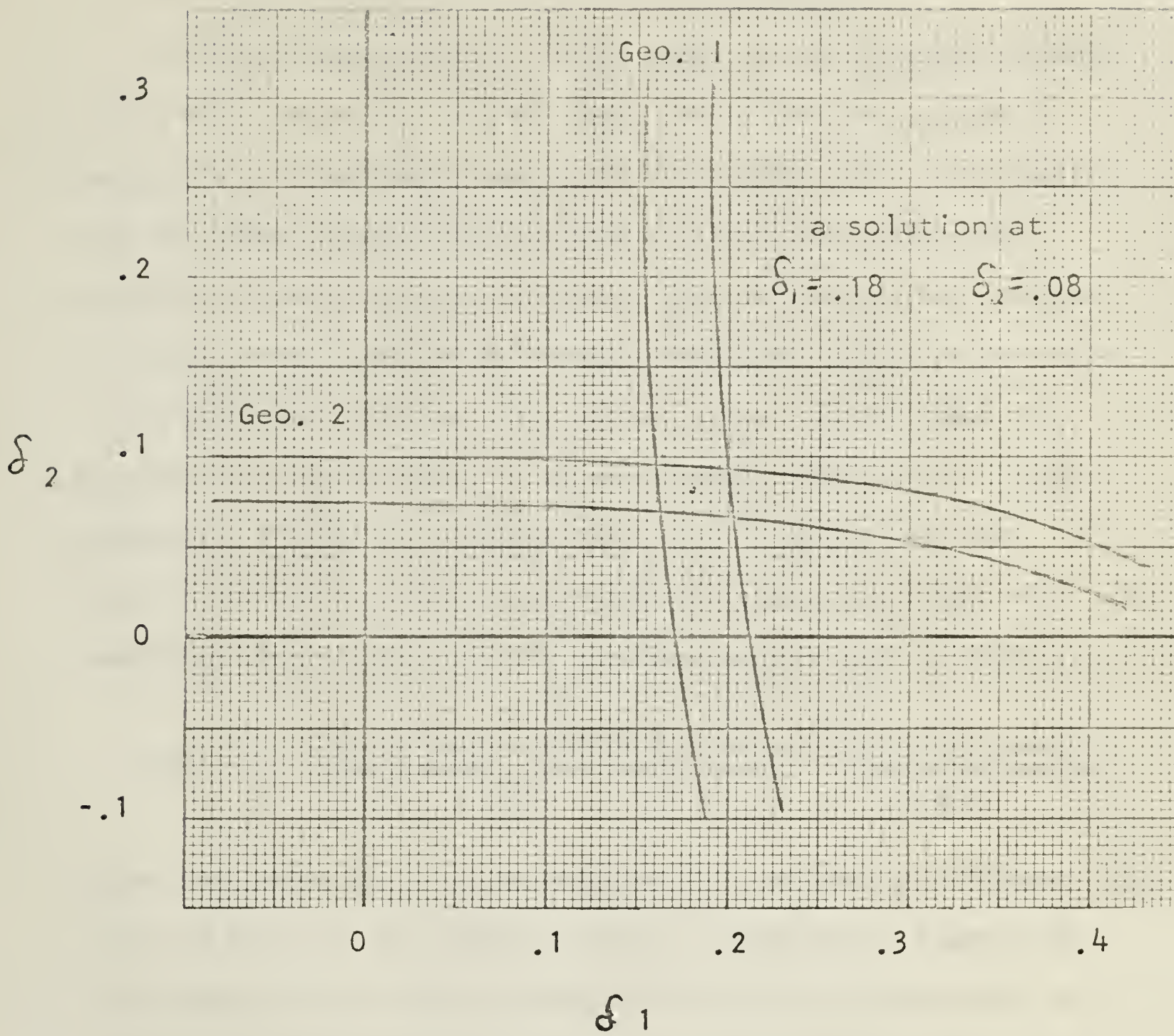


FIG. 3-27

γ_1 VERSUS γ_2 FOR THE GAMMA-GAMMA CORRELATIONS.

(d) The Distribution of the 1.40 MeV Gamma Ray

The distribution of the 1.40 MeV gamma ray was measured simultaneously with that of the 1.75 MeV gamma ray so that the population parameters are identically equal. It was pointed out a little earlier that the gamma ray distributions were of little value since the population parameters were not known. This problem has been overcome for the 1.40 MeV gamma ray by deriving reasonable values of the population parameters from the distribution of the 1.75 MeV gamma ray, population parameters used in the gamma-gamma correlations. If the parameters, $P'(3/2) = 0.32$ and $P'(5/2) = 0.12$ are put into the equation for a $7/2$ to $5/2$ transition given in Appendix A with the assumption that $P'(7/2) = 0$, the predicted angular distribution is

$$W(\theta) = 1 - \frac{(.264 + 1.68\delta - .07\delta^2) P_2(\cos \theta)}{1 + \delta^2} + \frac{(.489)\delta^2 P_4(\cos \theta)}{1 + \delta^2}$$

Figure 3-28 shows how well the measured and predicted coefficients agree and indicates the possible range of values of δ . Figure 3-29 illustrates that the best agreement is obtained from the smaller of the two δ 's resulting from the quadratic relationship. This value of δ is $+ 0.176$.

(e) The Branching Ratio of the 1.75 MeV Level.

An experiment was performed to determine the relative probability of the 1.75 MeV level decaying to the ground state. This requires a method to determine the amount of summing occurring in the system due

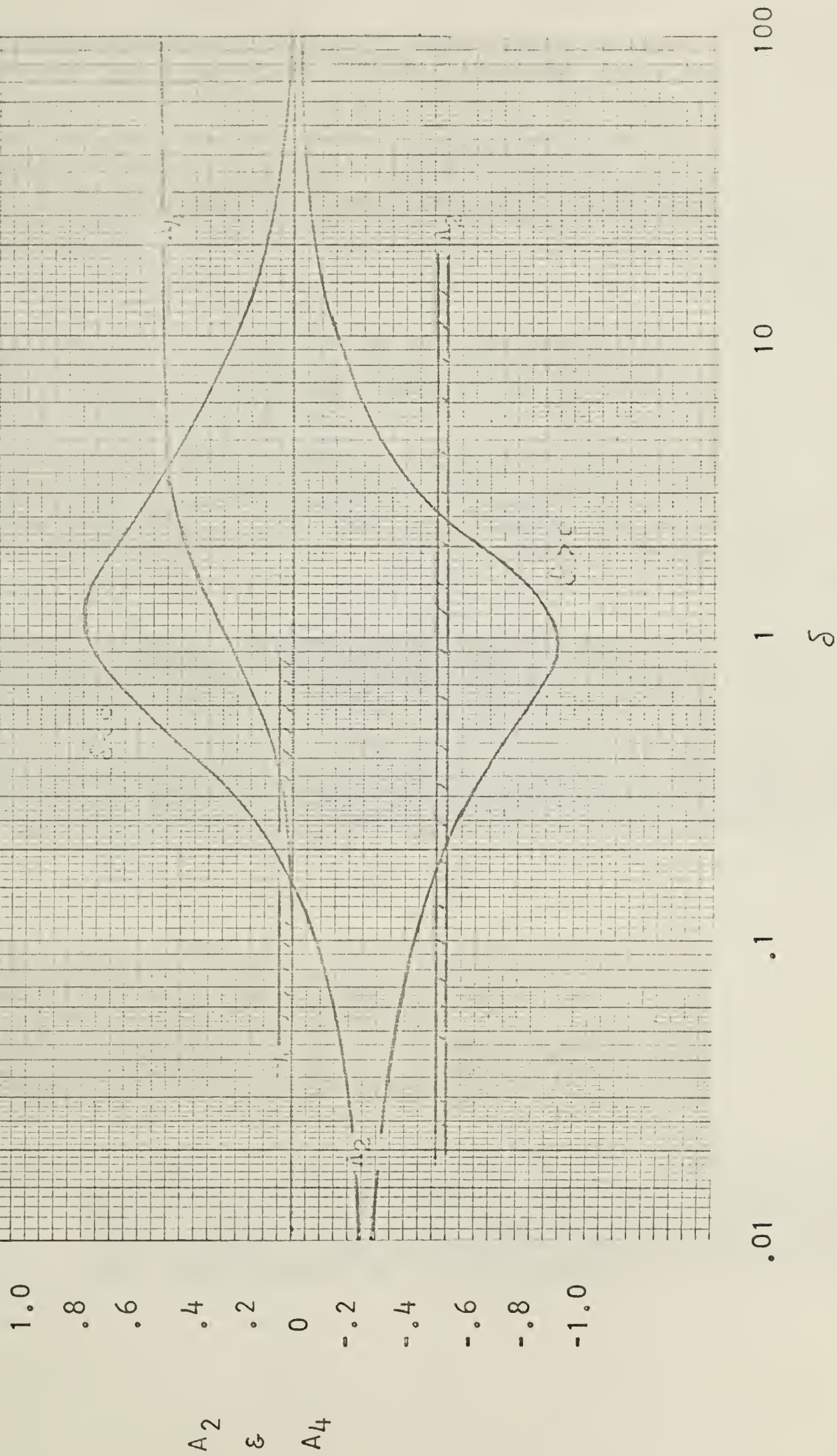


FIG. 3-28

A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING $P'(3/2) = .32$ AND $P'(5/2) = .12$ FOR A SPIN CHANGE OF $7/2$ TO $5/2$. THE SHADED BARS ARE THE EXPERIMENTAL RANGES OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.40 MEV GAMMA RAY DISTRIBUTION.

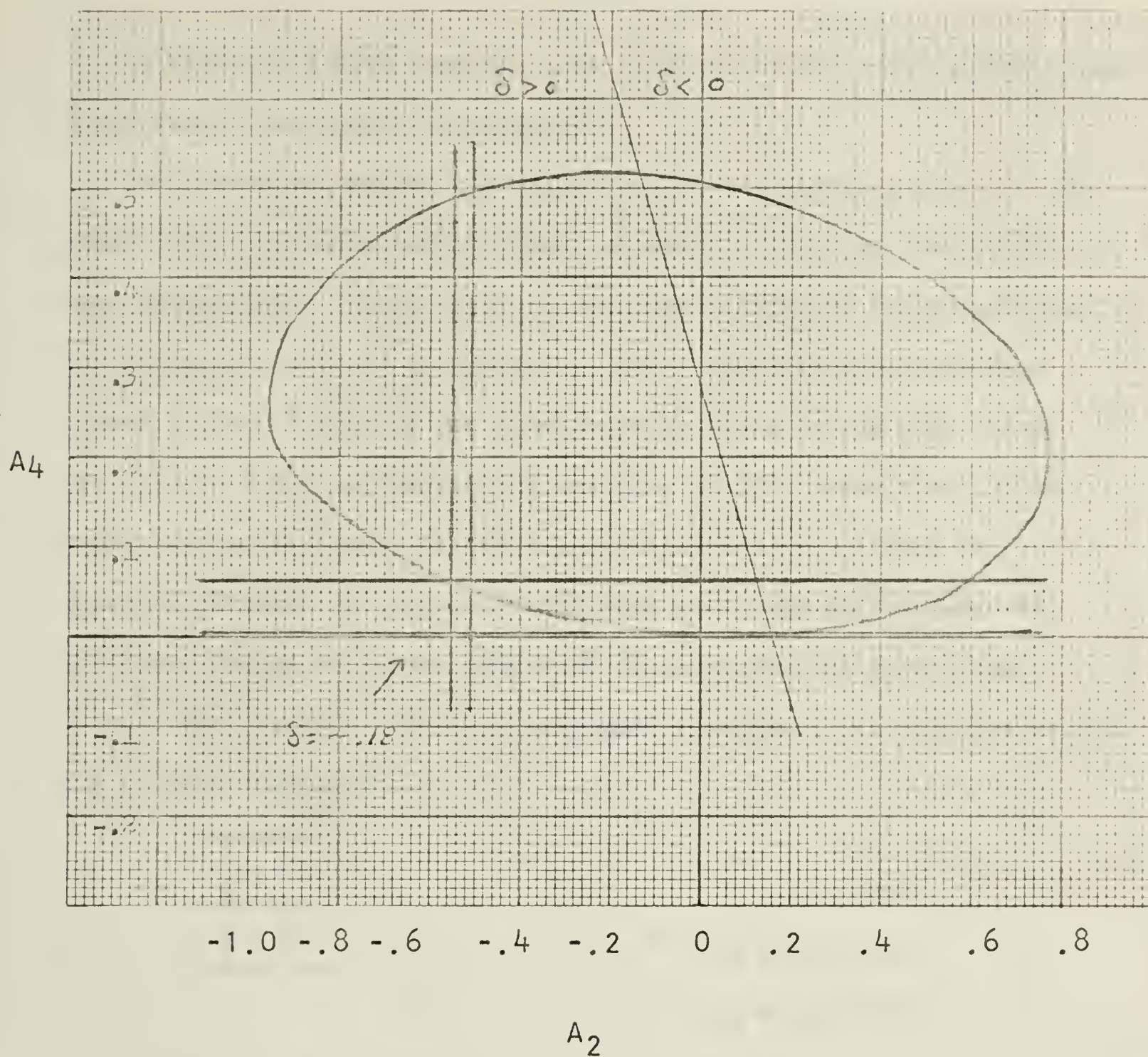
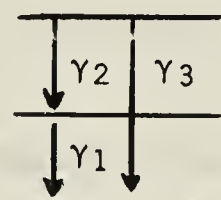


FIG.3-29 A PLOT OF A_2 VERSUS A_4 FOR ALL VALUES OF δ FOR A $7/2$ TO $5/2$ SPIN CHANGE, ASSUMING $P'(3/2) = .32$ AND $P'(5/2) = .12$. THE CROSSED BARS ARE THE MEASURED VALUES OF A_2 AND A_4 FOR THE 1.40 MEV GAMMA RAY, TAKEN FROM THE DISTRIBUTION.

to the relatively high counting rate of the 0.35 MeV and 1.40 MeV gamma rays, some of which are coincident.

An absorption method was used in which the counting rates of the gamma rays with and without a lead absorber in front of the crystal were determined. The sum peak is much more sensitive to the absorber, for the probability of absorption is the product of the individual probabilities of each of the gamma rays involved in the sum. With the 3 in. x 3 in. NaI crystal at an angle of 30° , where the 1.75 MeV gamma ray has a maximum in the distribution and at a target to detector distance of 15.9 cm., runs were made with and without the absorber. Eight runs were made with the absorber and eight runs without the absorber, the two being done alternately to minimize errors due to gain drifts, etc.



$$\gamma_1 = 0.35 \text{ MeV}$$

$$\gamma_2 = 1.40 \text{ MeV}$$

$$\gamma_3 = 1.75 \text{ MeV}$$

Let n_i be the measured counting rate of gamma ray i .

Then

$$n_i = N_i \epsilon_i W_i \pm X$$

where

N_i = the true disintegration rate via gamma ray i

ϵ_i = the full energy peak efficiency for gamma ray i
in the 3 in. x 3 in. NaI crystal

W_i = the measured distribution of gamma ray i

X = the sum counting rate in the system.

The experimental counting rates of each gamma ray without the absorber may be represented by:

$$n_1 = N_1 \epsilon_1 W_1 - X \quad n_2 = N_2 \epsilon_2 W_2 - X \quad n_3 = N_3 \epsilon_3 W_3 + X.$$

The experimental counting rates of each gamma ray with the absorber may be represented by:

$$n_1' = N_1 \epsilon_1' W_1 - X' \quad n_2' = N_2 \epsilon_2' W_2 - X' \quad n_3' = N_3 \epsilon_3' W_3 + X'$$

$$\epsilon_1' = e^{-\mu_1 \rho} \epsilon_1$$

Since X contains the product $\epsilon_1 \epsilon_2$, then X' may be written as $X' = e^{-(\mu_1 + \mu_2) \rho} X$.

The μ 's are the mass absorption coefficients given by Davisson (Da 55).

$$\mu_1 = 0.293 \quad \mu_2 = 0.056 \quad \mu_3 = 0.0497$$

The thickness of the lead, ρ , is 3.932 gm/cm ; this gives the following.

$$e^{-\mu_1 \rho} = 0.3160 \quad e^{-\mu_2 \rho} = 0.8023 \quad e^{-\mu_3 \rho} = 0.8225 \quad e^{-(\mu_1 + \mu_2) \rho} = 0.2540$$

The counting rates with the absorber may now be represented as:

$$n_1' = 0.316 N_1 \epsilon_1 W_1 - .254 X \quad n_2' = .802 N_2 \epsilon_2 W_2 - .254 X$$

$$n_3' = .822 N_3 \epsilon_3 W_3 + .254 X$$

The experimental relative counting rates normalized to neutron monitor counts are:

$$\begin{array}{ll} n_1 = 1.7690 \pm .0168 & n_1' = 0.5980 \pm 0.0124 \\ n_2 = 0.3300 \pm .0059 & n_2' = 0.2676 \pm 0.0055 \\ n_3 = 0.0335 \pm .0026 & n_3' = 0.0221 \pm 0.0024 \end{array}$$

The following ratios may be formed:

$$\frac{n_2}{n_3} = \frac{N_2 \epsilon_2 W_2 - X}{N_3 \epsilon_3 W_3 + X} = \frac{0.3300}{0.0335} = 9.85$$

$$\frac{n_2'}{n_3'} = \frac{.802 N_2 \epsilon_2 W_2 - .254 X}{.822 N_3 \epsilon_3 W_3 + .254 X} = \frac{0.2676}{0.0221} = 12.1$$

giving

$$N_2 \epsilon_2 W_2 - 9.85 N_3 \epsilon_3 W_3 - 10.85 X = 0$$

$$.802 N_2 \epsilon_2 W_2 - 9.95 N_3 \epsilon_3 W_3 - 3.329 X = 0$$

Solving these simultaneously for N_2/N_3

$$\frac{N_2}{N_3} = 14.00 \frac{\epsilon_3 W_3(30^\circ)}{\epsilon_2 W_2(30^\circ)}$$

$$W_3(\theta) = 1 + .368 P_2(\cos \theta) - .2 P_4(\cos \theta)$$

$$W_2(\theta) = 1 - .53 P_2(\cos \theta)$$

$$\epsilon_3 = 0.00295$$

$$\epsilon_2 = 0.00370$$

$$W_3(30^\circ) = 1.216$$

$$N_2/N_3 = 20.4 \pm 5$$

$$W_2(30^\circ) = 0.670$$

$$\frac{I_{1.75}}{I_{1.75} + I_{1.40}} = \frac{N_3}{N_3 + N_2} = .046 \pm .015$$

where

I_i is the intensity of gamma ray i .

3.3 The 2.87 MeV Level

This level has two gamma rays in coincidence with the neutrons feeding it. They are a 1.12 MeV gamma ray to the 1.75 MeV level and a 2.52 MeV gamma ray to the 0.35 MeV level. These gamma rays were also in time coincidence with the gamma rays coming from these last two levels. An n-gamma correlation with the neutron counter at zero degrees was measured at a bombarding energy of 5.50 MeV and the distributions of these gamma rays were measured at the same energy. These can be seen in Figures 3-30 and 3-40. On the assumption that the substates $m = \pm 1/2$ are predominantly populated due to the geometry, the same procedure in analysis can be made as used on the gamma rays from the lower levels.

(a) The 1.12 MeV Gamma Ray

Since a correlation far from isotropy is measured for the 1.12 MeV gamma ray, $A_2 = -0.6 \pm 0.117$ and $A_4 = +0.121 \pm 0.143$, a spin of $1/2$ can be eliminated immediately for the 2.87 MeV level.

Assuming the 1.75 MeV level to be $7/2$, a spin change of $3/2$ to $7/2$ is not ruled out since there is an overlap in the predicted and measured value of A_2 as indicated by Figure 3-31. The predicted A_4 coefficient

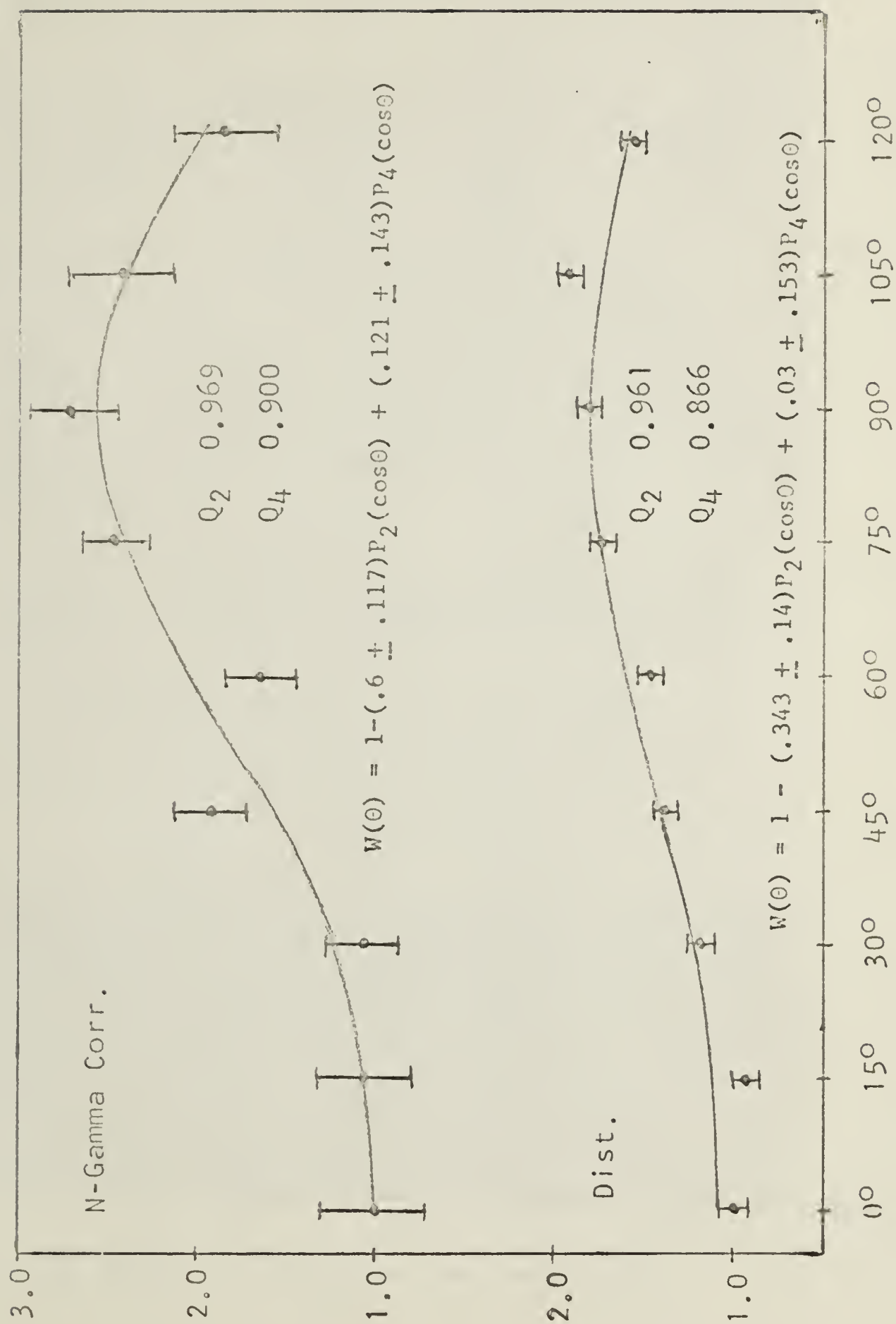


FIG. 3-30 THE N-GAMMA CORRELATION AND DISTRIBUTION OF THE 1.12 MEV GAMMA RAY AT A BOMBARDING ENERGY OF 5.50 MEV.

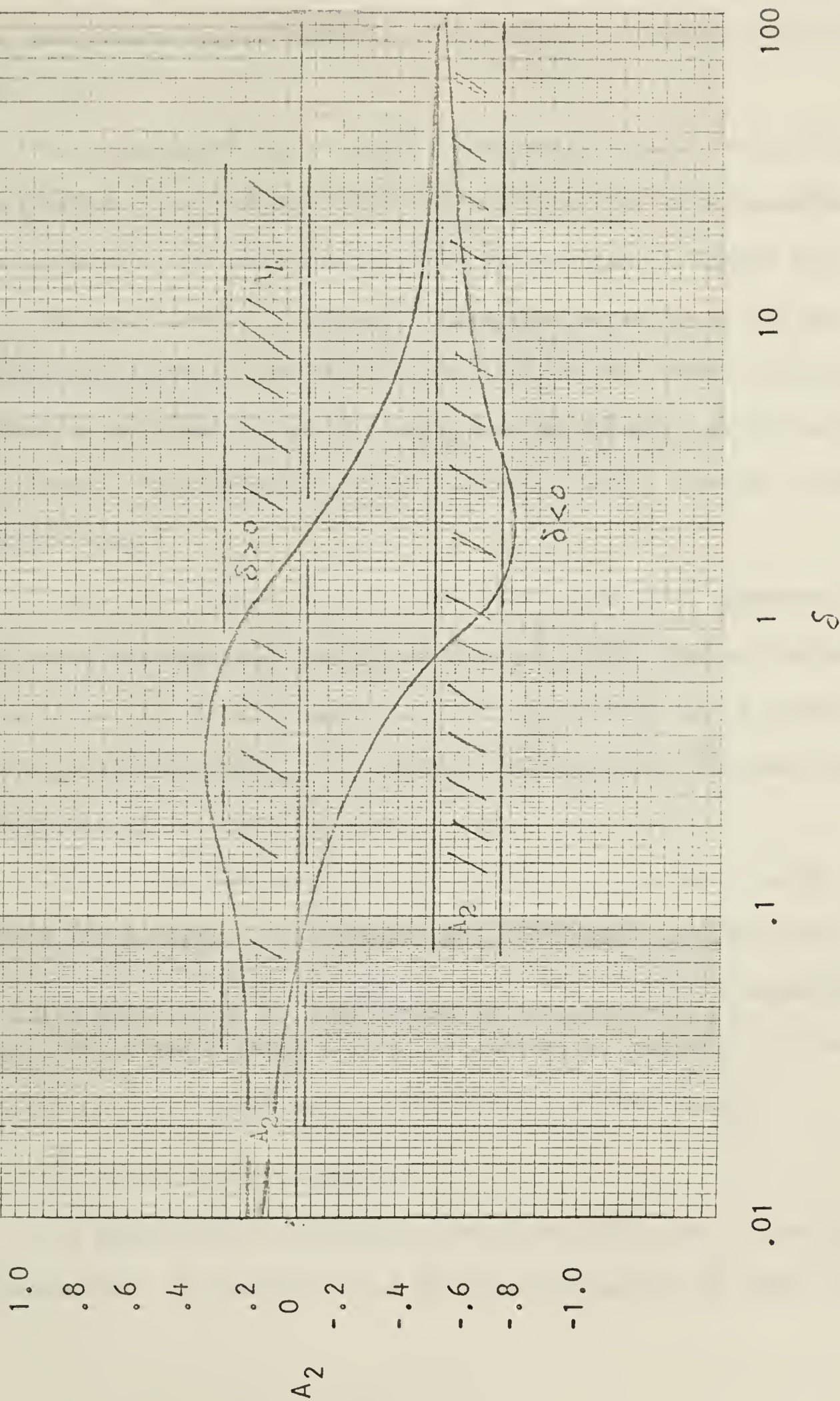


FIG. 3-31 A PLOT OF A_2 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $3/2$ TO $7/2$. THE SHADED BAR IS THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 COEFFICIENT FOR THE 1.12 MEV GAMMA RAY. THE A_4 IS PREDICTED TO BE ZERO.

is zero for a spin of $3/2$ and the measured value is quite large, but the uncertainty in the measured value allows the possibility of A_4 being zero.

The possibility of a $5/2$ to $7/2$ transition is shown in Figure 3-32. The predicted and measured coefficients agree giving a possible δ of approximately $-.34$ and -8.0 which is illustrated in Figure 3-33.

The spin change of $7/2$ to $7/2$ does not agree in A_2 or A_4 as is illustrated by Figure 3-34. The possibility of a small $P(3/2)$ contribution is ruled out for it would tend to make the predicted A_2 coefficient less negative. This would rule out a spin of $7/2$ for the 2.87 MeV level.

A spin of $9/2$ for the 2.87 MeV level gives good agreement between predicted and measured coefficients as is illustrated in Figure 3-35. This allows a δ of approximately $+.136$ as illustrated in Figure 3-36. Figure 3-37 indicates that a slight $P(3/2)$ contribution would not affect the value of δ very much.

A spin combination of $11/2$ to $7/2$ has no agreement in the predicted and measured coefficients as illustrated by Figure 3-38. A small $P(3/2)$ contribution does not alter the predicted correlation very much as can be seen from the equations of Appendix A. This rules out the possibility of spin $11/2$ for the 2.87 MeV level.

(b) The 2.52 MeV Gamma Ray

The measured n - γ correlation and distribution are illustrated in Figure 3-40. The anisotropy of the 2.52 MeV gamma ray rules out a

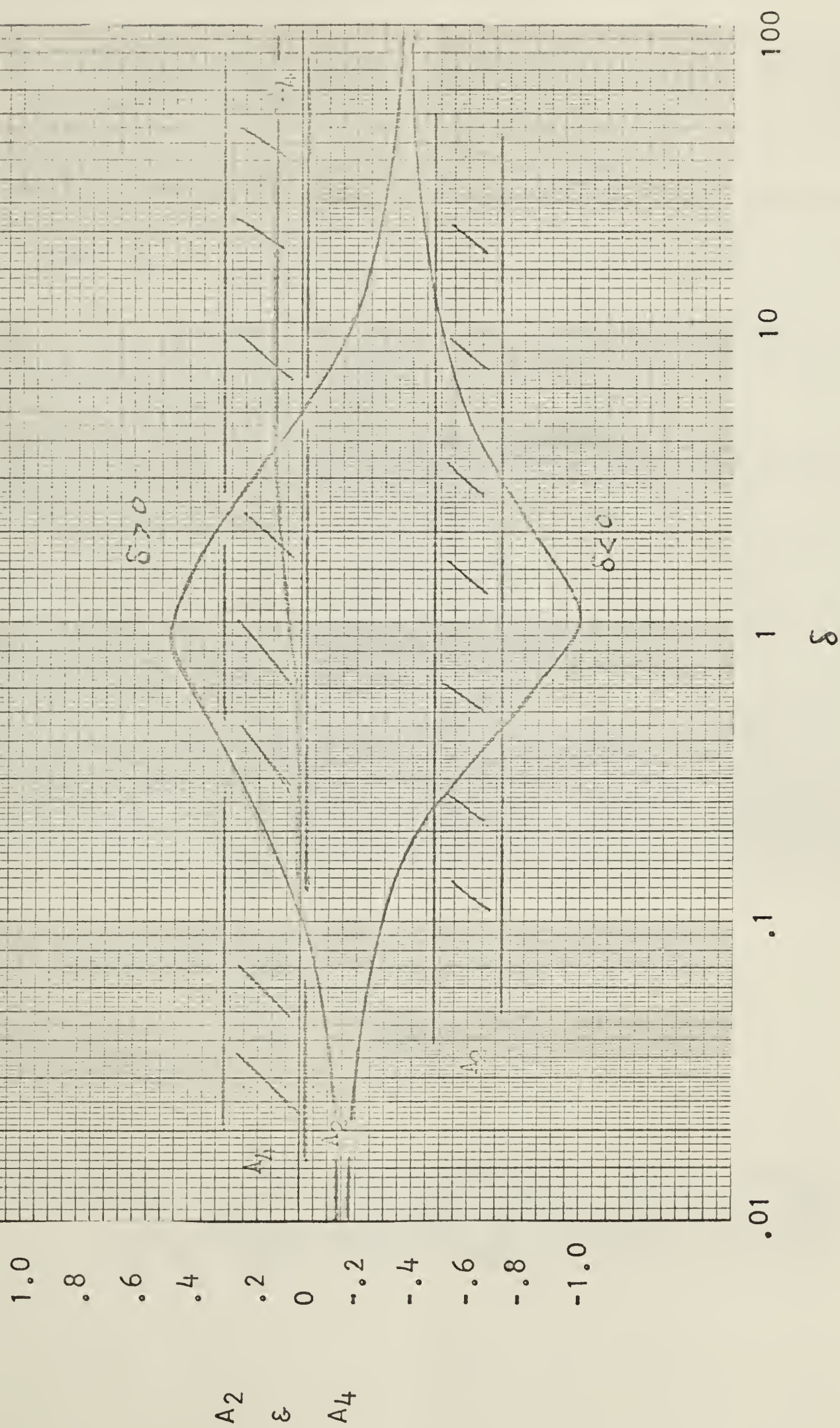


FIG. 3-32 A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING $P(\frac{1}{2})$ ONLY, FOR A SPIN CHANGE OF $5/2$ TO $7/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.12 MEV GAMMA RAY.

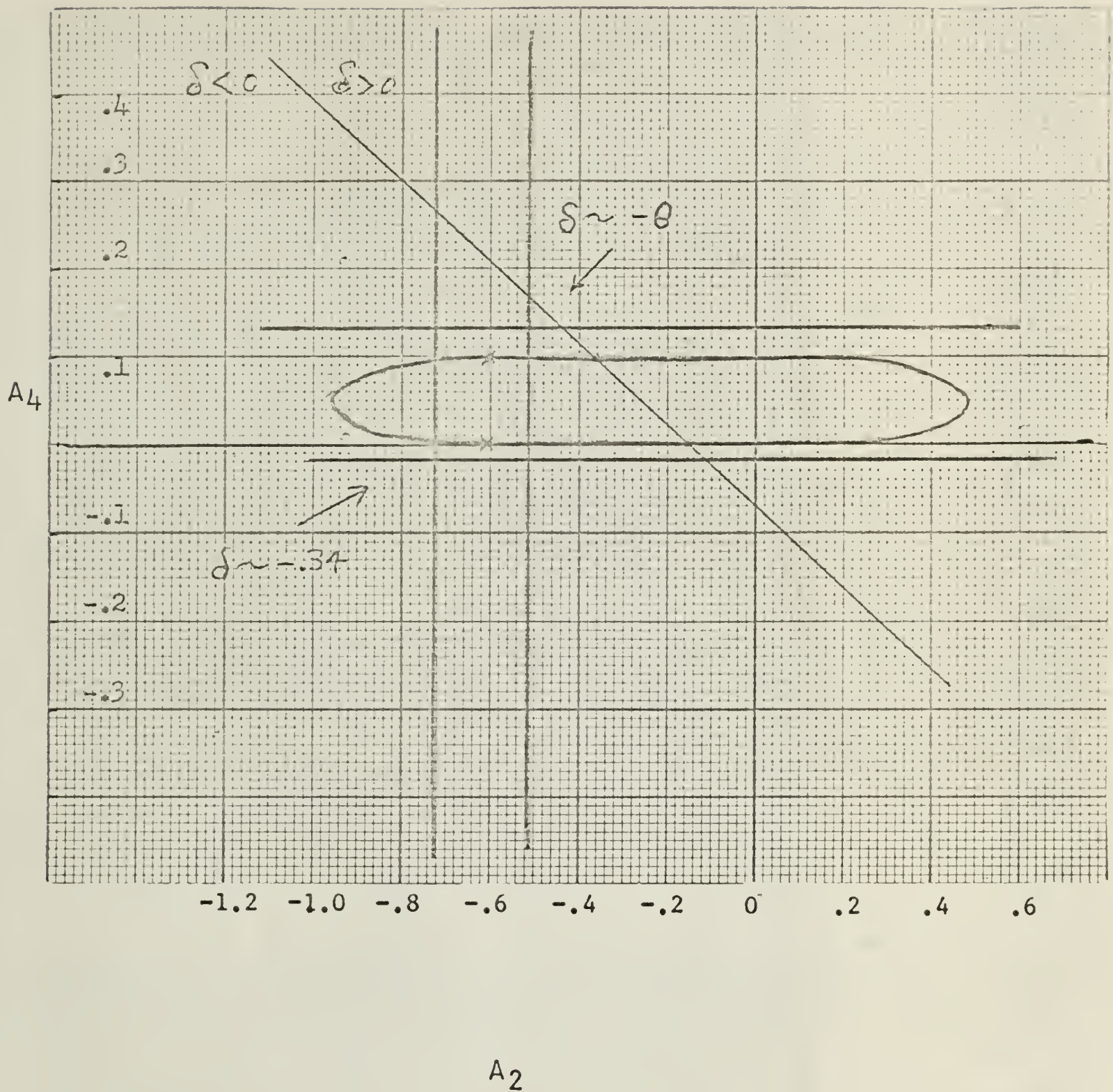


FIG. 3-33 A PLOT OF A_2 VERSUS A_4 FOR ALL VALUES OF δ FOR A $5/2$ TO $7/2$ SPIN CHANGE, ASSUMING ONLY $P(\frac{1}{2})$. THE CROSSED BARS ARE THE MEASURED VALUES OF A_2 A_4 FOR THE 1.12 MEV GAMMA RAY.

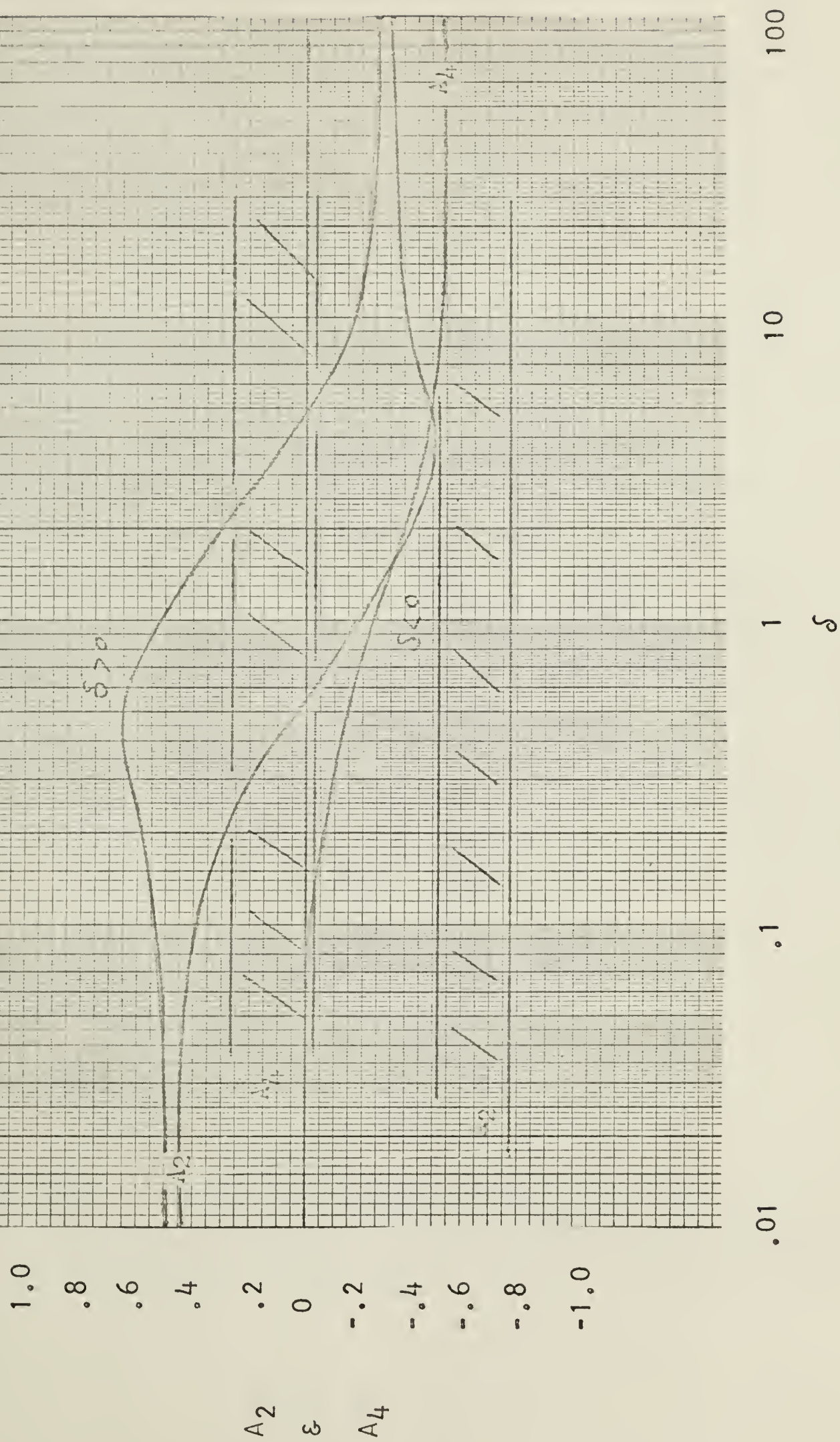


FIG. 3-34 A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $7/2$ TO $7/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.12 MEV GAMMA RAY.

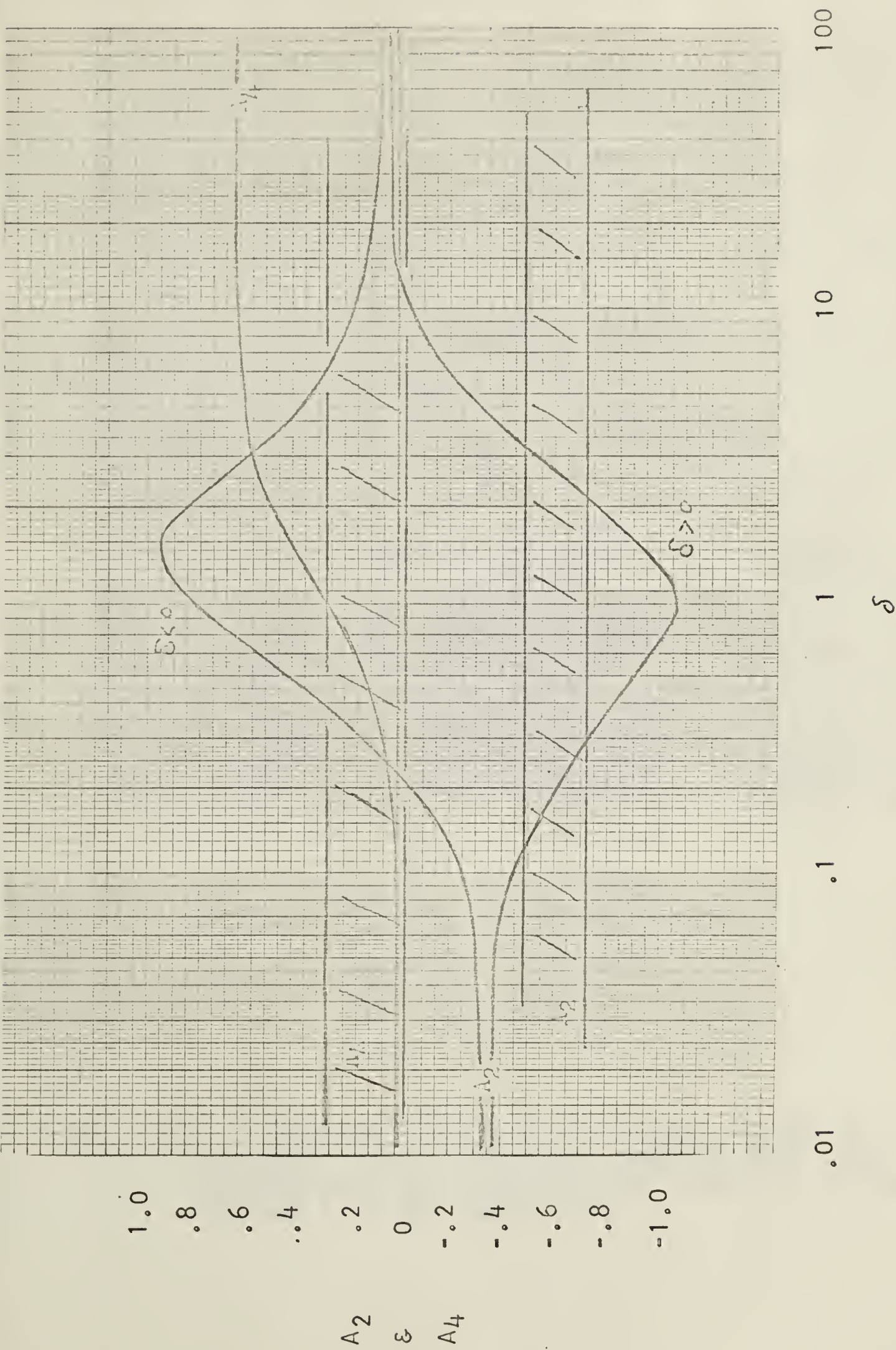


FIG. 3-35

A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $9/2$ TO $7/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.12 MEV GAMMA RAY.

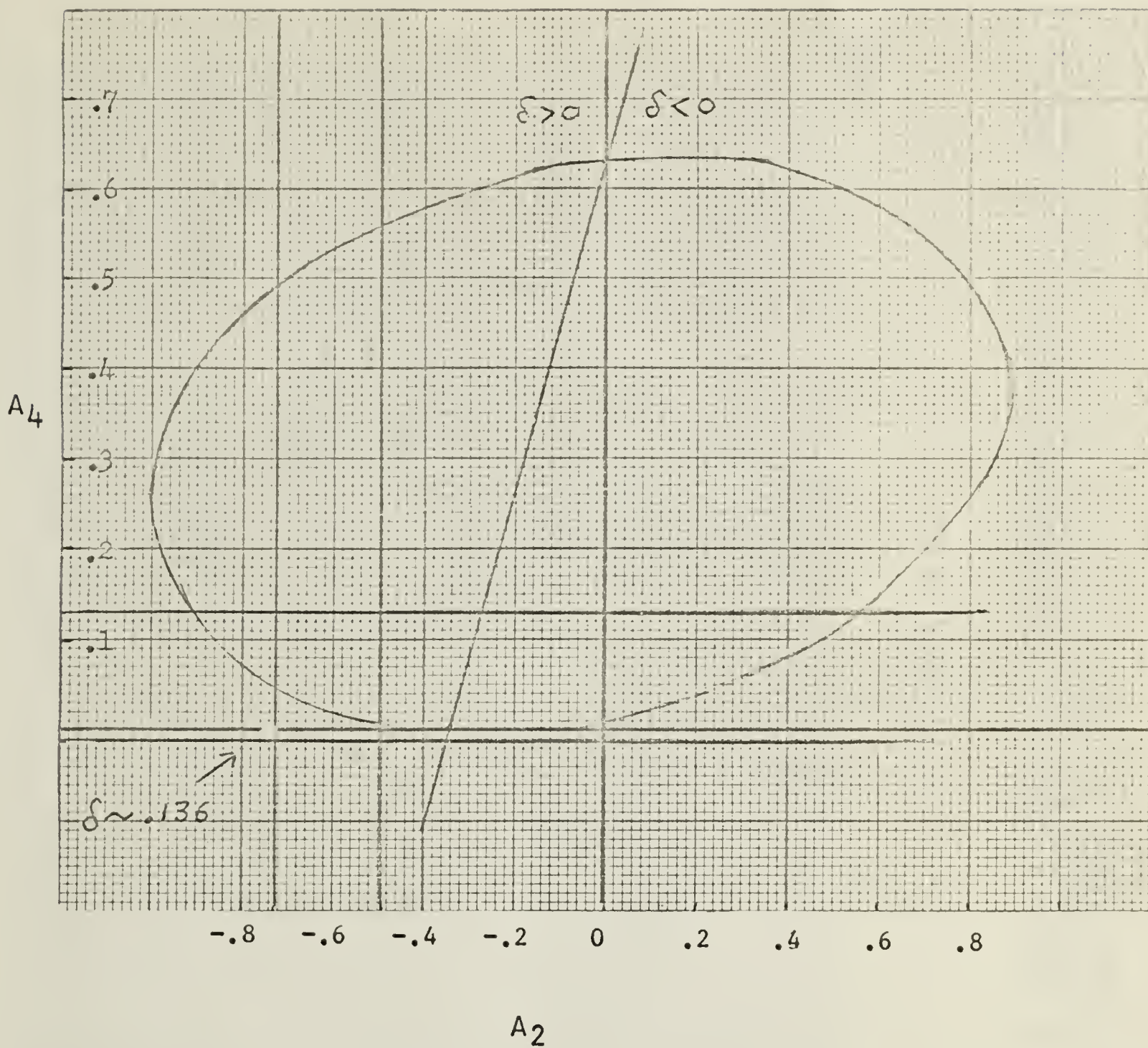


FIG. 3-36 A PLOT OF A_2 VERSUS A_4 FOR ALL VALUES OF δ FOR A $9/2$ TO $7/2$ SPIN CHANGE, ASSUMING ONLY $P(\frac{1}{2})$. THE CROSSED BARS ARE THE MEASURED VALUES OF A_2 AND A_4 FOR THE 1.12 MEV GAMMA RAY.

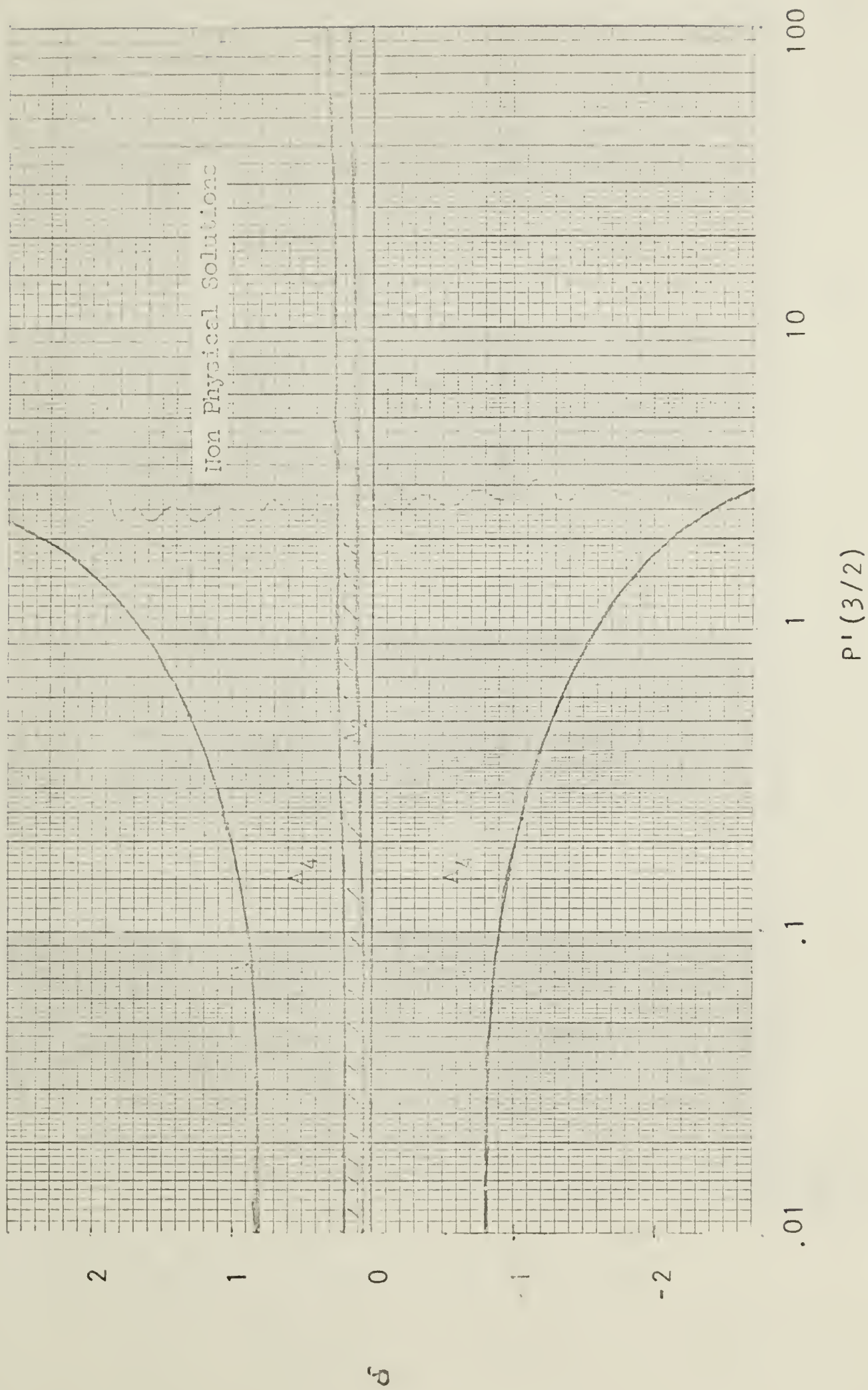


FIG. 3-37 A PLOT OF δ VERSUS $P'(3/2)$ USING THE MEASURED VALUES OF A_2 AND A_4 FOR THE 1.12 MEV GAMMA RAY AND THE PREDICTED COEFFICIENTS² FOR A $9/2$ TO $7/2$ SPIN CHANGE.

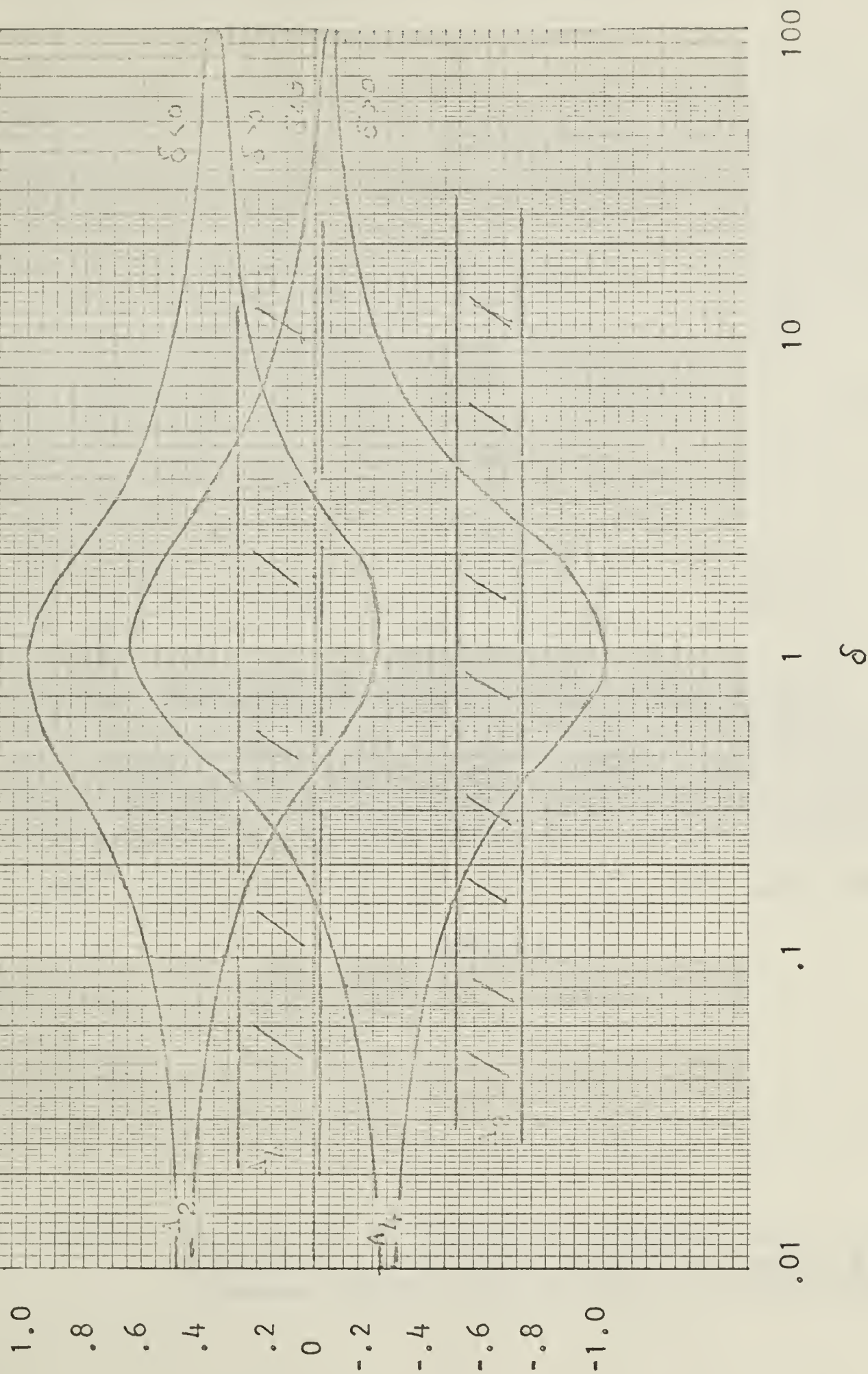


FIG. 3-38 A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $11/2$ TO $7/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 1.12 MEV GAMMA RAY.

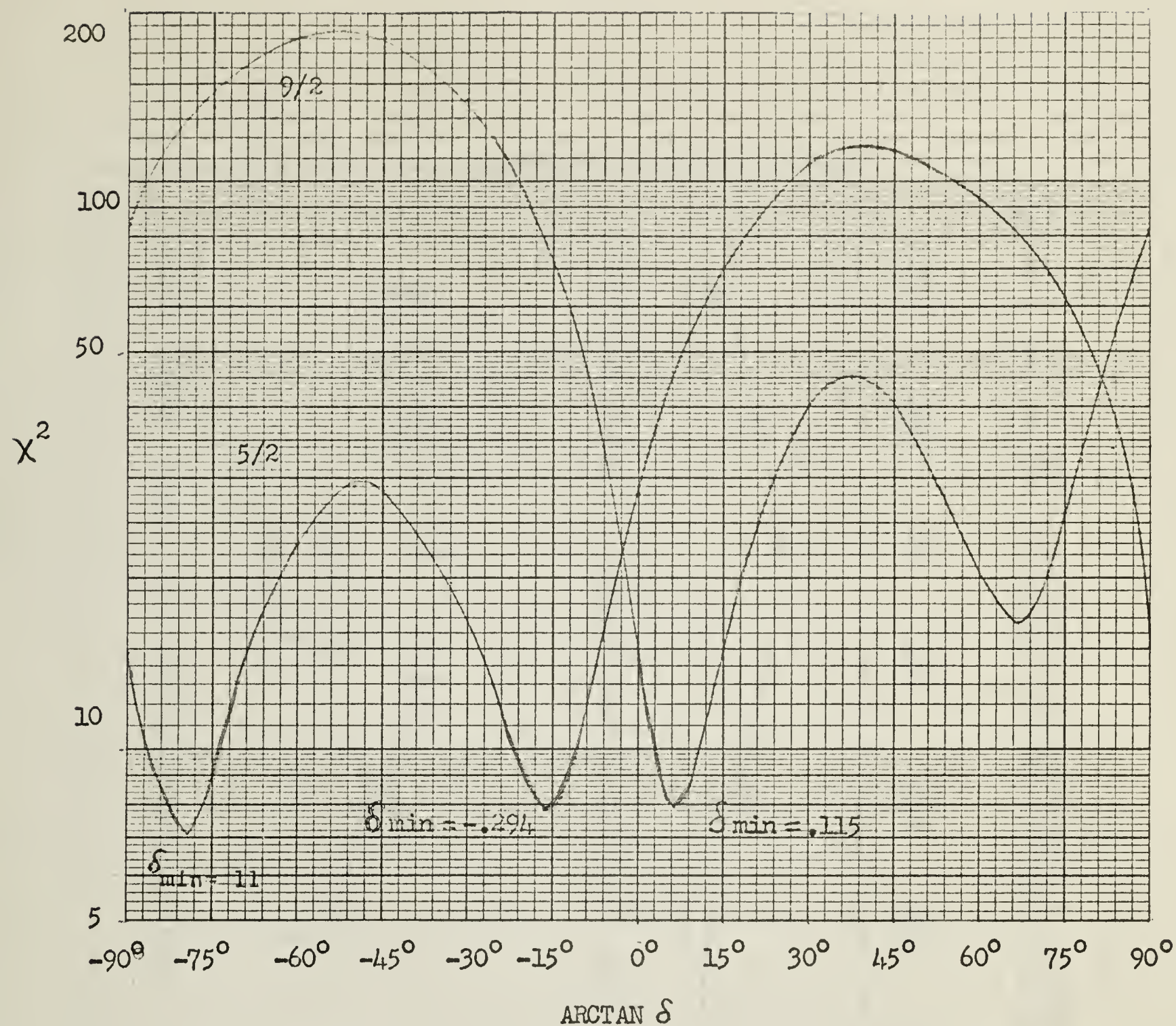


FIG. 3-39

A PLOT OF χ^2 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A $5/2$ TO $7/2$ AND $9/2$ TO $7/2$ SPIN CHANGE WITH THE N-GAMMA CORRELATION OF THE 1.12 MEV GAMMA RAY.

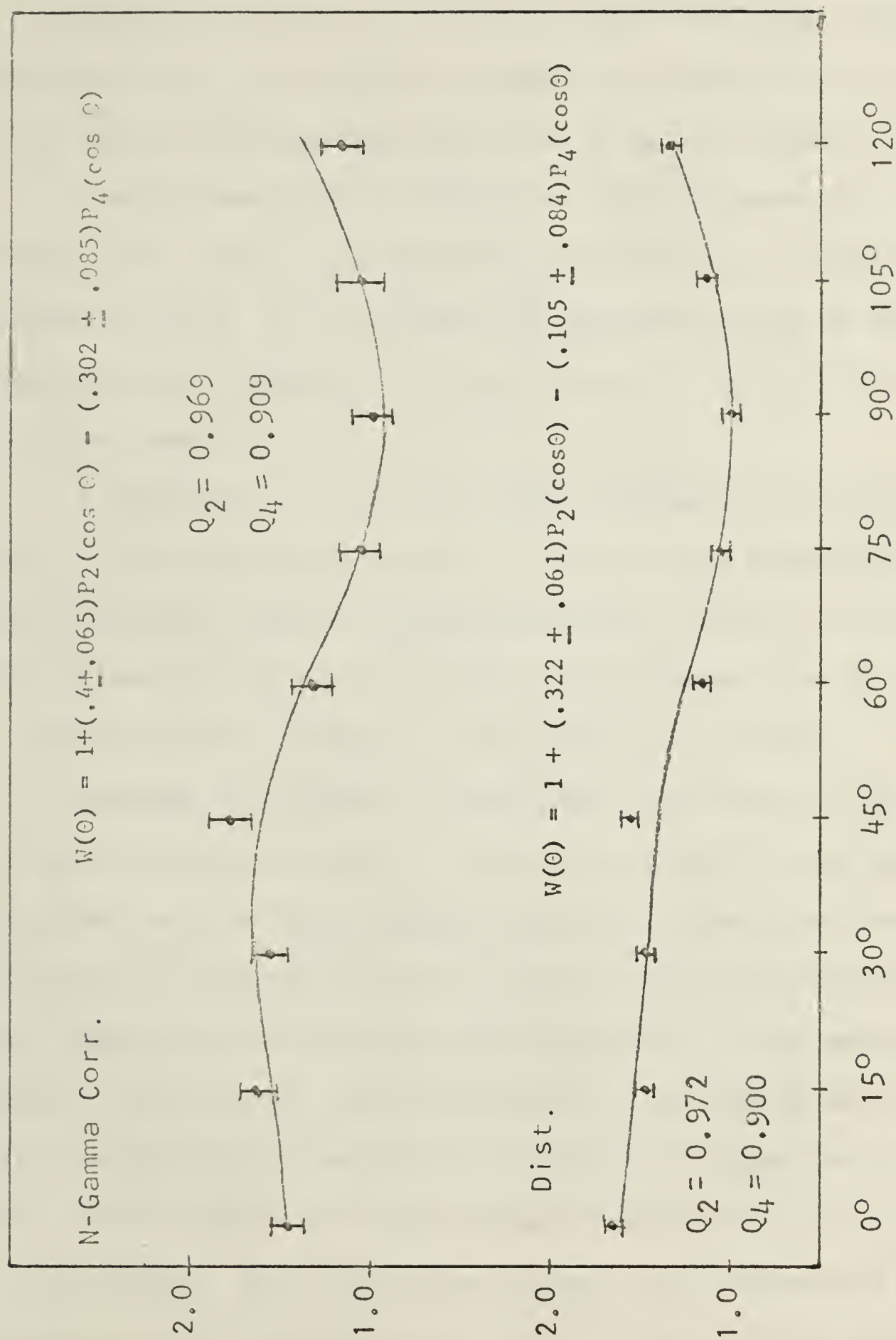


FIG. 3-40 THE N-GAMMA CORRELATION AND DISTRIBUTION OF THE 2.52 MEV GAMMA RAY AT A BOMBARDING ENERGY OF 5.50 MEV.

spin of $1/2$ while a substantial measured A_4 coefficient rules out the possibility of a $3/2$ spin.

Assuming a spin of $5/2$ for the 0.35 MeV level, one finds good agreement for a $5/2$ to $5/2$ spin change as illustrated by Figure 3-41. This allows a δ of approximately -1.85 as is illustrated by Figure 3-42.

A spin change of $7/2$ to $5/2$ agrees with the measured A_2 coefficient but not with A_4 as illustrated in Figure 3-43. A small contribution in $P(3/2)$ will not improve the agreement as can be seen from the equations of Appendix A. This rules out a spin of $7/2$ for the 2.87 MeV level.

A combination of $9/2$ to $5/2$ gives agreement in both coefficients as is illustrated in Figure 3-44. A contribution from $P(3/2)$ does not affect the value of δ appreciably until $P'(3/2) \geq 0.2$ as is illustrated in Figure 3-45. Figure 3-46 indicates that the more probable of the two delta's is the smaller, $\delta = + 0.035$.

Possible 1.05 MeV and 2.45 MeV gamma rays from the 2.80 MeV level are isotropic since, as discussed in Chapter I, the spin of the 2.80 MeV level is firmly established as $1/2$. Howard and co-workers (Ho 65) have indicated that the 2.80 MeV level decays 10% by the 2.45 MeV gamma ray and 90% by the 2.80 MeV gamma ray. This means that even if the 2.80 MeV level is populated in the present reaction, there is a negligible 1.05 MeV gamma ray intensity and that the intensity of the 2.45 MeV gamma ray is small since it is only 10% of the total decay of that level. The illustration of Figure 2-14 indicates a 2.80 MeV gamma ray peak in the spectrum. Thus it can be expected that there are

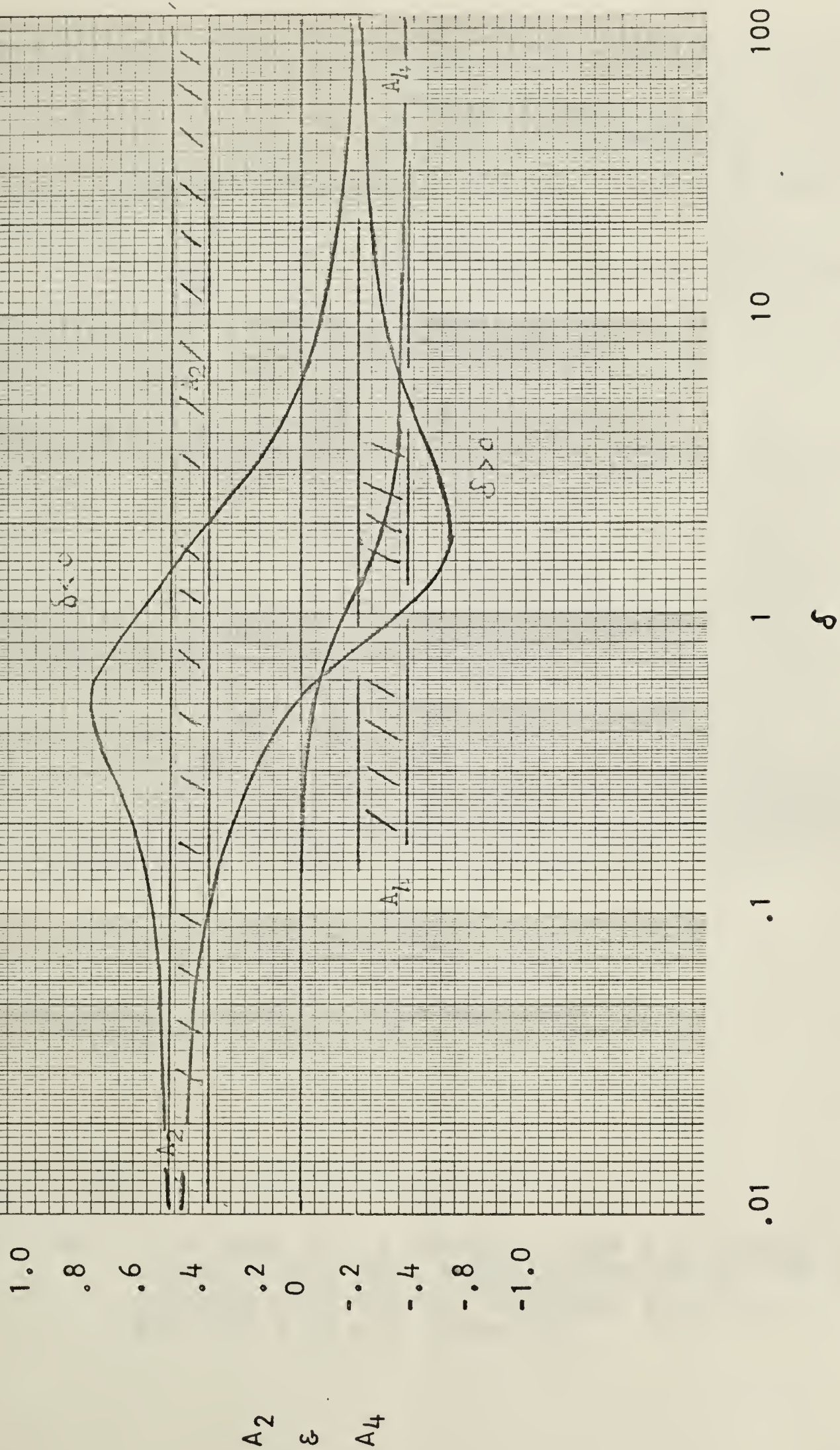


FIG. 3-41

A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $5/2$ TO $5/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 2.52 MEV GAMMA RAY.

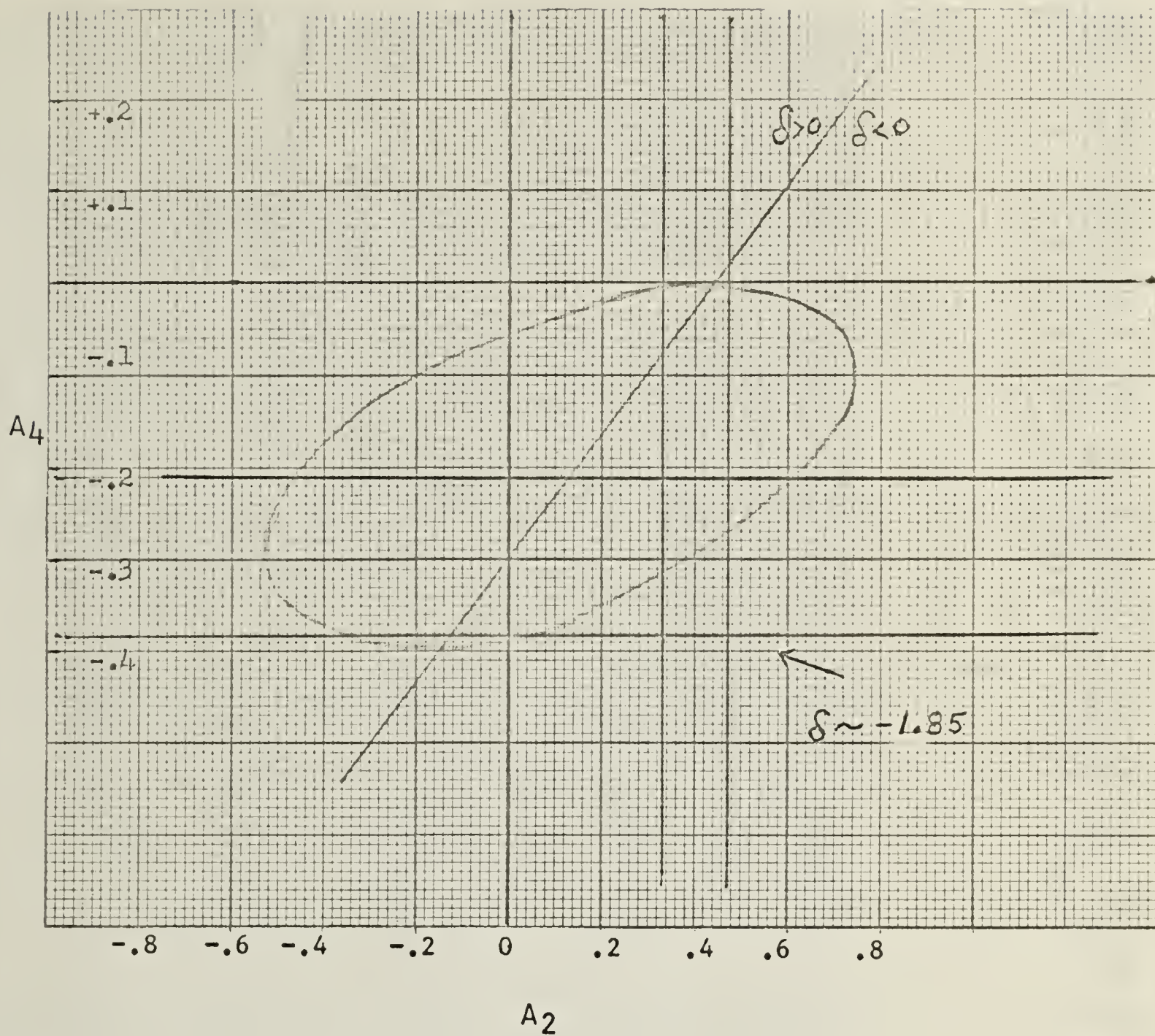


FIG. 3-42

A PLOT OF A_2 VERSUS A_4 FOR ALL VALUES OF δ FOR A $5/2$ TO $5/2$ SPIN CHANGE, ASSUMING ONLY $P(\frac{1}{2})$. THE CROSSED BARS ARE THE MEASURED VALUES OF A_2 AND A_4 FOR THE 2.52 MEV GAMMA RAY.

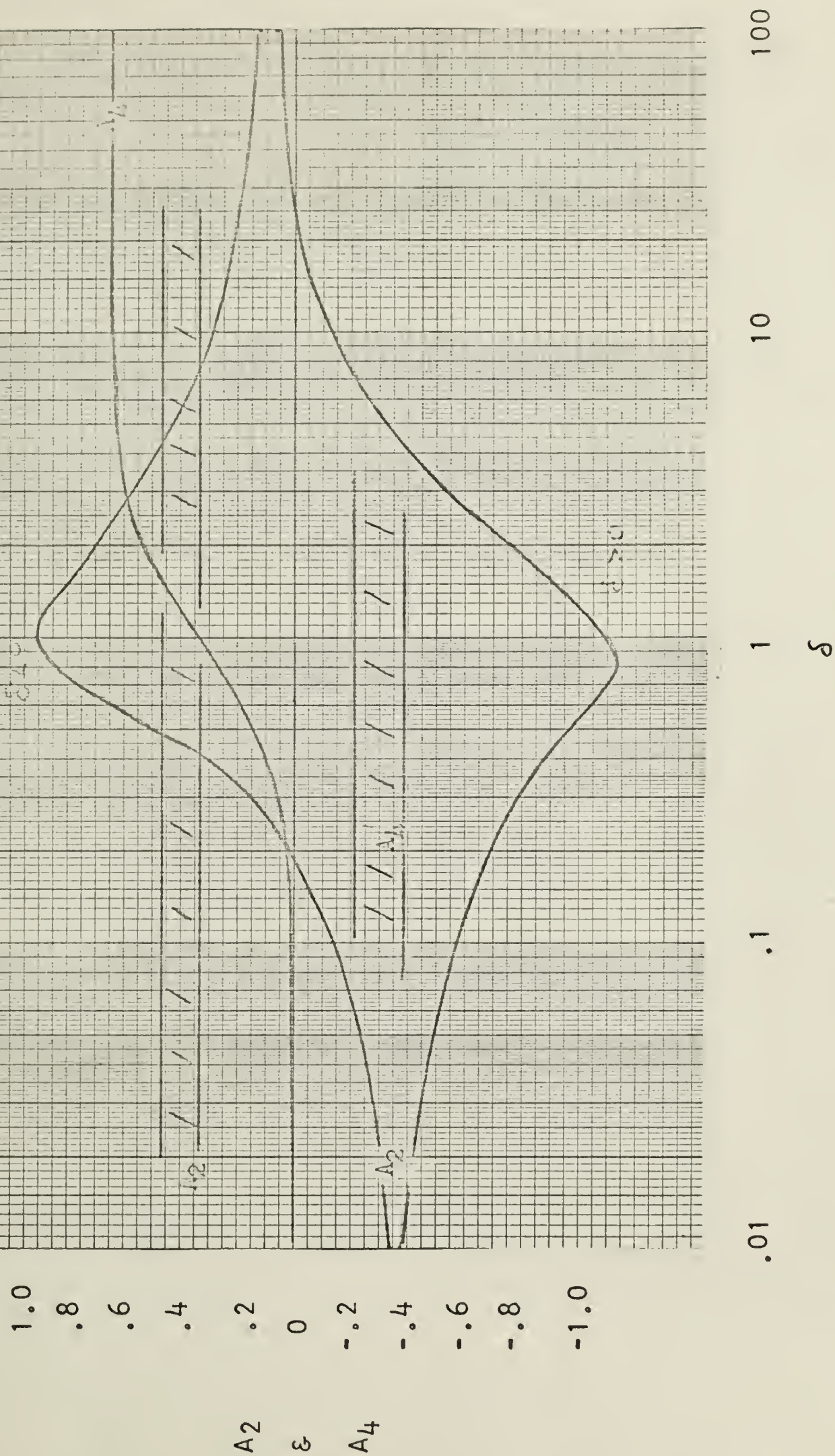


FIG. 3-43 A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $7/2$ TO $5/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 2.52 MEV GAMMA RAY.

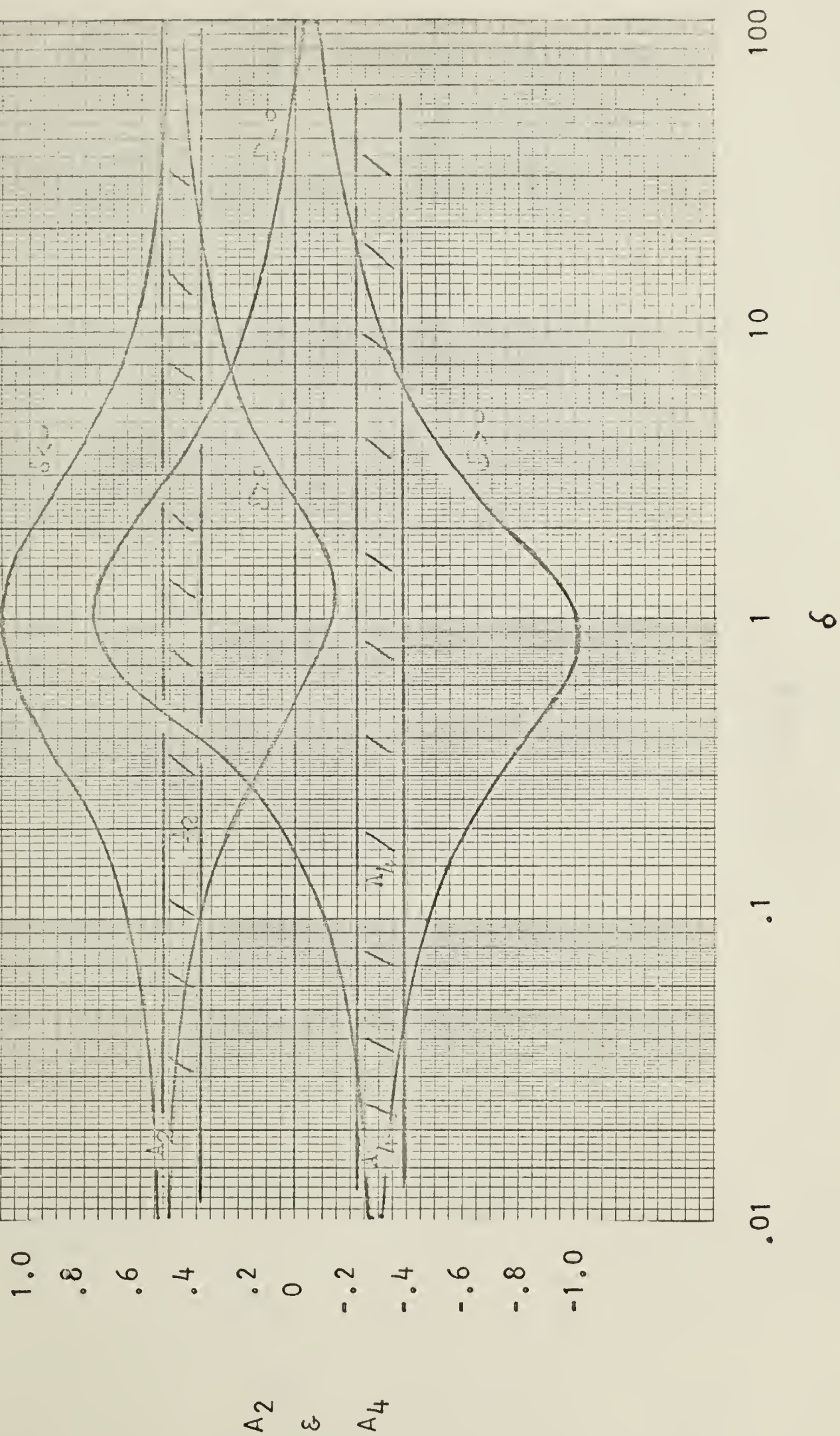


FIG. 3-44 A PLOT OF A_2 AND A_4 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A SPIN CHANGE OF $9/2$ TO $5/2$. THE SHADED BARS ARE THE EXPERIMENTALLY MEASURED RANGE OF THE A_2 AND A_4 COEFFICIENTS FOR THE 2.52 MEV GAMMA RAY.

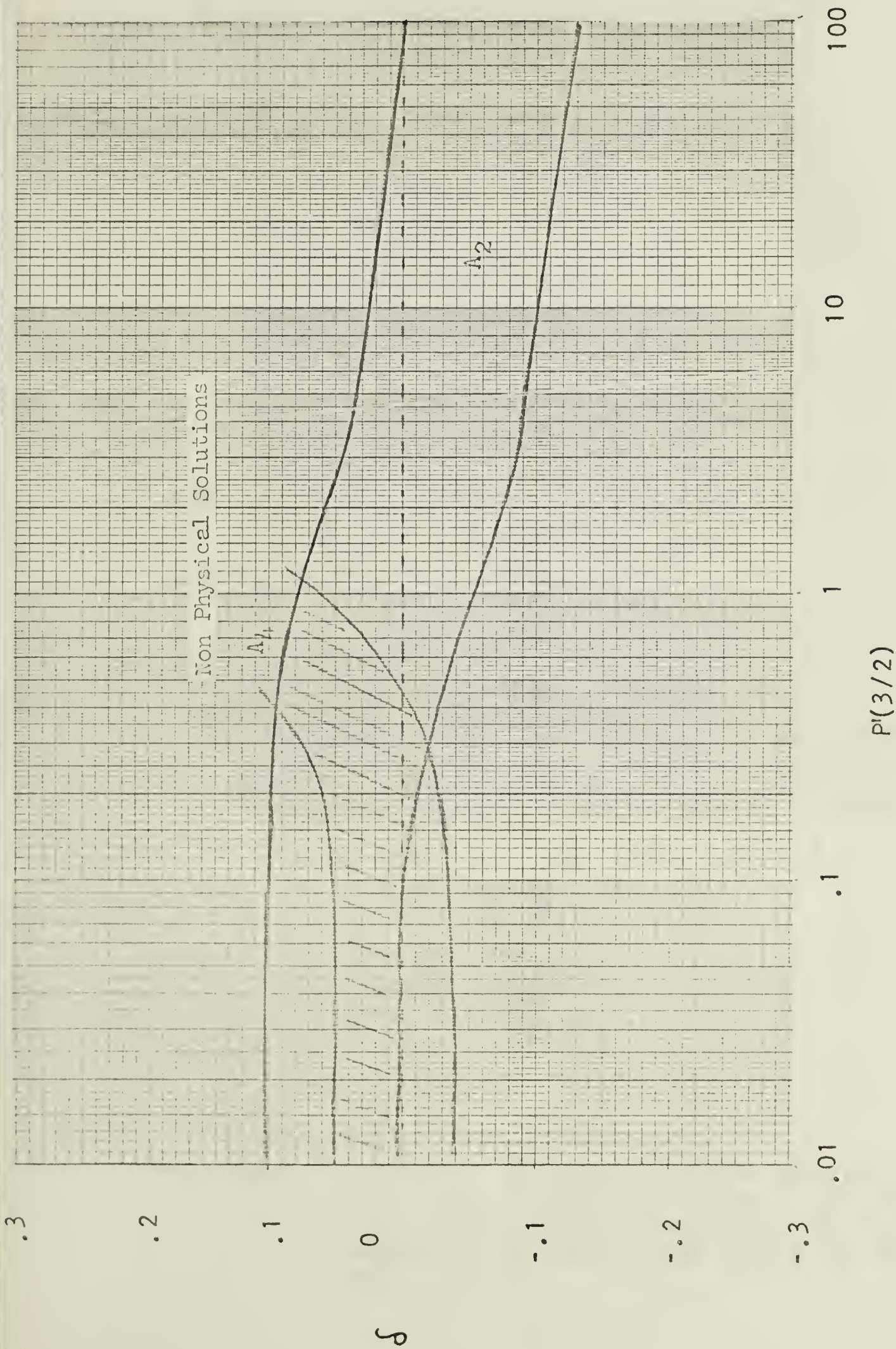


FIG. 3-45 A PLOT OF δ VERSUS $P(3/2)$ USING THE MEASURED VALUES OF A_2 AND A_4 FOR THE 2.52 MEV GAMMA RAY AND THE PREDICTED COEFFICIENTS FOR A $9/2$ TO $5/2$ SPIN CHANGE.

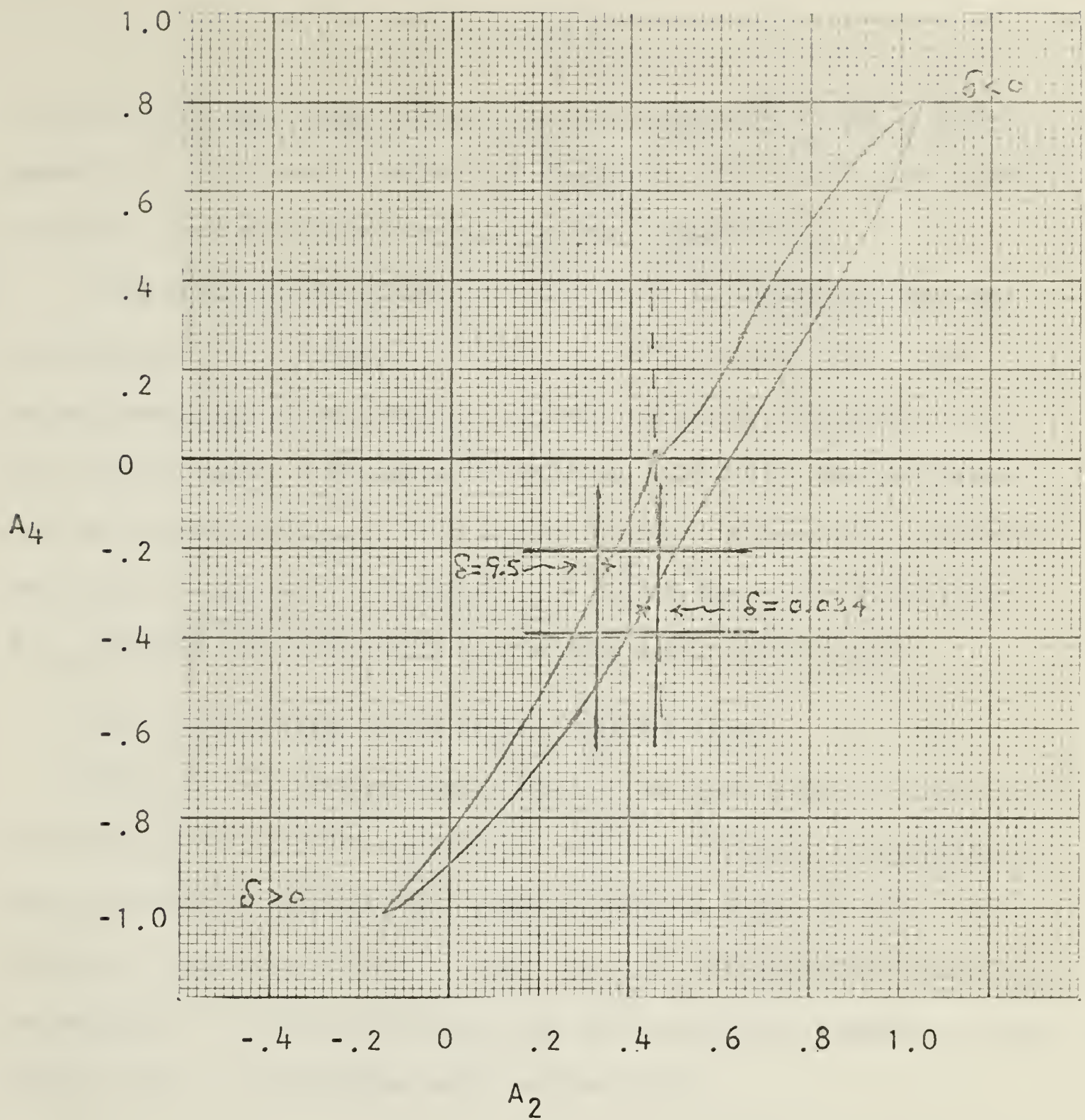


FIG. 3-46 A PLOT OF A_4 VERSUS A_2 FOR ALL VALUES OF δ FOR A $9/2$ TO $5/2$ SPIN CHANGE, ASSUMING ONLY $P(\frac{1}{2})$. THE CROSSED BARS ARE THE MEASURED VALUES OF A_4 AND A_2 FOR THE 1.12 MEV GAMMA RAY.

some 2.45 MeV gamma rays included in the photo-peak of the 2.52 MeV gamma ray. This has the effect of flattening the correlation slightly. There has been no correction made for this possibility.

From the analysis of the 1.12 MeV and 2.52 MeV gamma rays, one finds that a spin assignment of 5/2 or 9/2 for the 2.87 MeV level. All other possibilities are excluded by both or one or the other of the two correlations. A χ^2 analysis assuming only P(1/2) was performed and is plotted in Figures 3-39 and 3-47. The δ 's from this analysis are $\delta_{2.82} = +.034$ or $+ 9.5$ and $\delta_{1.12} = + .115$ for a spin of 9/2 and $\delta_{1.12} = -.294$ or $- 5.4$ and $\delta_{2.52} = - 1.88$ for a spin of 5/2.

(c) The Branching Ratio of the 2.87 MeV Level

Using the full energy peaks from the spectrum given in Figure 2-11, the efficiencies for a 3 in. x 3 in. NaI counter given in Appendix D, and the measured distributions given in Figures 3-30 and 3-40, the relative intensities of the 1.12 MeV and 2.52 MeV gamma ray have been calculated. The counter distance was 15.9 cm. and the counter was situated at 45°. The following ratio may be formed.

$$\frac{n_{1.12}}{n_{2.52}} = \frac{N_{1.12} \epsilon_{1.12} W_{1.12}}{N_{2.52} \epsilon_{2.52} W_{2.52}}$$

where

n_i = the measured counting rate of gamma ray i.

N_i = the actual disintegration rate of gamma ray i.

ϵ_i = the full energy peak efficiency for a 3 in. x 3 in. NaI crystal and gamma ray i.

W_i = the measured correlation of gamma ray i.



FIG. 3-47

A PLOT OF χ^2 VERSUS δ , ASSUMING ONLY $P(\frac{1}{2})$ FOR A 5/2 TO 5/2 AND 9/2 TO 5/2 SPIN CHANGE WITH THE N-GAMMA CORRELATION OF THE 2.52 MEV GAMMA RAY.

The experimental values of the relative counting rates are $n_{1.12} = 86 \pm 5$ and $n_{2.52} = 20 \pm 3$.

This gives

$$\frac{n_{1.12}}{n_{2.52}} = 4.4 \pm 0.8$$

Using $W_{1.12}(\theta) = 1 - .6 P_2(\cos \theta) + .12 P_4(\cos \theta)$

$$W_{2.52}(\theta) = 1 + .4 P_2(\cos \theta) - .3 P_4(\cos \theta)$$

$$\epsilon_{1.12} = .0084$$

$$\epsilon_{2.52} = .0021$$

one gets

$$\frac{N_{1.12}}{N_{2.52}} = 1.68 \pm .31$$

and

$$\frac{N_{1.12}}{N_{1.12} + N_{2.52}} = .37 \pm .04$$

This indicates that the 2.87 MeV level decays 37% via the 1.12 MeV gamma if there is no contribution from the 2.45 MeV gamma ray in the 2.52 MeV peak. Since there is no way of knowing what the exact contribution of the 2.45 MeV level is, a lower limit of .37 is all that can be known with certainty.

3.3 Discussion

It is advantageous to examine the experimental spectroscopic parameters in the light of the independent particle model; some of the ambiguities in the assignments can be removed by appealing to theory.

Wilkinson (Wi 60) has devised a procedure for analyzing the transitions in terms of collected empirical data. By forming the unit, $|M|^2$, in Weisskopf units which is a comparison of the actual partial radiative width of a transition to the width calculated using the Weisskopf single particle estimates, one has a measure of how differently the nucleus behaves from the single particle model. Wilkinson (Wi 60) and van der Leun (Le 64) have tabulated these $|M|^2$ values for E1, M1, E2 and M2 transitions where the nature of the transition has been established.

For quadrupole-dipole mixing:

$$|M|_{E1}^2 = \frac{\Gamma(E1)}{\Gamma_w(E1)} = \frac{1}{1 + \delta^2} \frac{\Gamma}{\Gamma_w(E1)} \quad \text{where } \delta^2 = \frac{\Gamma(M2)}{\Gamma(E1)}$$

$\Gamma(E1)$ = measured partial radiative width for the transition.

$\Gamma_w(E1)$ = the Weisskopf estimate.

Γ = the measured total radiative width for the transition.

$$|M|_{M1}^2 = \frac{\Gamma(M1)}{\Gamma_w(M1)} = \frac{1}{1 + \delta^2} \frac{\Gamma}{\Gamma_w(M1)} \quad \delta^2 = \frac{\Gamma(E2)}{\Gamma(M1)}$$

$$|M|_{E2}^2 = \frac{\Gamma(E2)}{\Gamma_w(E2)} = \frac{\delta^2}{1 + \delta^2} \frac{\Gamma}{\Gamma_w(E2)} \quad \delta^2 = \frac{\Gamma(E2)}{\Gamma(M1)}$$

$$|M|_{M2}^2 = \frac{\Gamma(M2)}{\Gamma_w(M2)} = \frac{\delta^2}{1 + \delta^2} \frac{\Gamma}{\Gamma_w(M2)} \quad \delta^2 = \frac{\Gamma(M2)}{\Gamma(E1)}$$

Similar relationships may be formed for octupole-quadrupole mixing. The radiative width may be expressed in terms of τ , the mean lifetime, $\tau = \hbar/\Gamma$ where 1 eV is equivalent to 6.6×10^{-16} sec.

The Weisskopf partial radiative widths may be written as:

$$\begin{aligned} \Gamma_w(E1) &= 6.6 \times 10^{-2} A^{2/3} E_\gamma^3 \text{ eV} & \Gamma_w(M2) &= 1.5 \times 10^{-8} A^{2/3} E_\gamma^5 \text{ eV} \\ \Gamma_w(M1) &= 2.1 \times 10^{-3} A^0 E_\gamma^3 \text{ eV} & \Gamma_w(E3) &= 2.3 \times 10^{-14} A^2 E_\gamma^7 \text{ eV} \\ \Gamma_w(E2) &= 4.9 \times 10^{-8} A^{4/3} E_\gamma^5 \text{ eV} & \Gamma_w(M3) &= 6.8 \times 10^{-15} A^{4/3} E_\gamma^7 \text{ eV} \end{aligned}$$

Where

A = atomic number of the emitting nucleus, and

E_γ = gamma ray energy in MeV.

From these equations the values of Γ_w for the gamma rays studied in this experiment are: (all widths in eV)

	0.35 MeV	1.12 MeV	1.40 MeV	1.75 MeV	2.52 MeV
$\Gamma_w(E1)$	0.022	0.722	1.42	--	8.3
$\Gamma_w(M1)$	0.0009	0.029	5.7×10^{-2}	--	3.36
$\Gamma_w(E2)$	1.42×10^{-8}	5.0×10^{-6}	1.5×10^{-5}	4.8×10^{-5}	3.0×10^{-5}
$\Gamma_w(M2)$	0.057×10^{-8}	2.0×10^{-7}	6.14×10^{-7}	1.9×10^{-6}	1.2×10^{-5}
$\Gamma_w(E3)$	--	--	--	5.0×10^{-10}	6.3×10^{-9}
$\Gamma_w(M3)$	--	--	--	2.10×10^{-11}	2.5×10^{-10}

A list of the mean lives and corresponding radiative widths measured for the gamma rays considered is tabulated below.

γ -ray	τ (sec)	Γ (eV)	Reference
0.35 MeV	6.2×10^{-11}	1.06×10^{-5}	(Kh 59) (Ho 65)
1.40 MeV	1.1×10^{-13}	6.00×10^{-3}	(Be 63)
1.75 MeV	2.6×10^{-12}	2.50×10^{-4}	*
1.12 MeV	2.0×10^{-13}	3.30×10^{-3}	(Be 63)
2.52 MeV	4.6×10^{-13}	1.42×10^{-3}	(Be 63)

*This value is based on the lifetime of the 1.40 MeV gamma ray and the branching ratio found in this experiment.

The values for the multipole mixing ratios are listed in the following table.

γ -ray	δ
0.35 MeV	$+0.08 \pm 0.02$
1.40 MeV	$+0.18 \pm 0.02$
1.75 MeV	$+0.03 \pm 0.04$ or $+7 \pm 3.0$
1.12 MeV $5/2 \rightarrow 7/2$	-0.3 ± 0.1 or -10 ± 3.0
1.12 MeV $9/2 \rightarrow 7/2$	$+0.13 \pm 0.06$
2.52 MeV $5/2 \rightarrow 5/2$	-1.85 ± 0.25
2.52 MeV $9/2 \rightarrow 5/2$	$+0.035 \pm 0.045$ or $+9 \pm 3.0$

$|M|^2$ values calculated from the data presented in the last three tables are presented below for each gamma ray.

Considering the 0.35 MeV level,

0.35 MeV $5/2 \rightarrow 3/2^+$

	E1	M1	E2	M 2
$ M ^2$	4.7×10^{-4}	1.1×10^{-2}	4.7	116

The $|M|^2$ values for M1, E1, and E2 show typical inhibition and enhancement factors (Wi 60) while the value for M2 is high. Since the ground state has positive parity the transition is probably an E2-M1 transition indicating positive parity for the 0.35 MeV level. This parity assignment concurs with the value obtained from stripping reactions as well as the value dictated by the Nilsson model.

Considering the 1.75 MeV level,

1.40 MeV $7/2 \rightarrow 5/2^+$

	E1	M1	E2	M2
$ M ^2$	3.1×10^{-3}	0.077	16.8	340

Once again the E1, M1, and E2 values show typical inhibition and enhancement factors while the M2 value is high, indicating an E2-M1 type of transition.

1.75 MeV $7/2 \rightarrow 3/2^+$

$ M ^2$	E2		M2
	$\delta = + 7$	3.8×10^{-3}	1.52×10^{-4}
	$\delta = +.03$	0.192	7.6×10^{-3}

In this case the experiment was unable to yield an unambiguous value for δ . One of these two may be eliminated by examining the $|M|^2$ values. The values for $|M|^2$ for M2 are a factor of 100 and 10, respectively, too low while the E2 value when using $\delta = 7$ is too low by a factor of a thousand. The value for E2 using $\delta = .03$ is typical and indicates a E2-M3 type of transition. It may be concluded from the analysis of both gamma rays that the $7/2$ state has positive parity. This is in agreement with the value obtained from other work as well as the value dictated by the Nilsson model.

The $|M|^2$ values for the 1.12 MeV gamma ray from the 2.87 MeV state are:

1.12 MeV Gamma Ray

δ	Spin Change	$ M _{E1}^2$	$ M _{M1}^2$	$ M _{E2}^2$	$ M _{M2}^2$
-10	$5/2 \rightarrow 7/2$	4.6×10^{-5}	1.1×10^{-3}	660	1.65×10^4
0.12	$9/2 \rightarrow 7/2$	4.54×10^{-3}	0.114	9.1	223
-0.3	$5/2 \rightarrow 7/2$	4.1×10^{-3}	0.103	54	1.35×10^3

The $|M|^2$ value for the case of $\delta = -10$ yields too great an inhibition factor for E1 and M1 transitions while the E2 enhancement is much too large. This eliminates the first combination shown in the above table. The E1 values for the remaining two combinations are typical where the average for this type of low energy transition is approximately 2×10^{-3} Weisskopf units. The values for M1 are also typical where the average value is 0.1 Weisskopf units. An examination of the E2 values indicates that the combination 9/2 to 7/2 has a value equal to the average for this type of transition and the value for the combination 5/2 to 7/2 is about a factor of 6 higher than the average. This analysis favours a spin change of 9/2 to 7/2 for the 1.12 MeV gamma ray with a E2-M1 mixing ratio of +0.12.

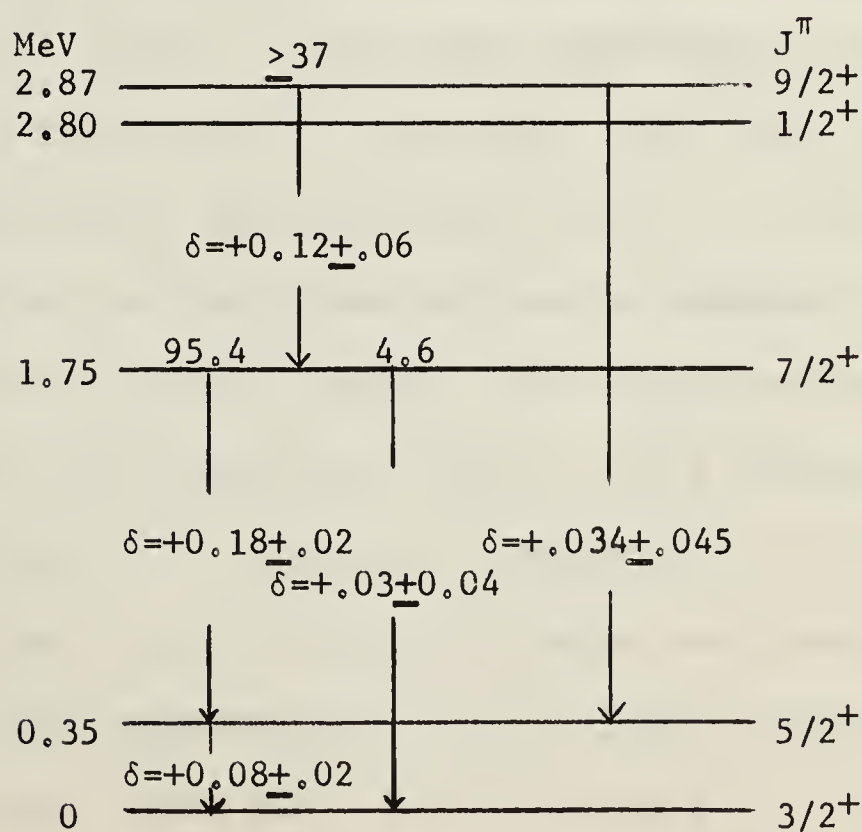
The $|M|^2$ values for the 2.52 MeV gamma ray from the 2.87 MeV state are:

2.52 MeV Gamma Ray

Spin Change	δ	$ M _{E1}^2$	$ M _{M1}^2$	$ M _{E2}^2$	$ M _{M2}^2$	$ M _{E3}^2$	$ M _{M3}^2$
5/2 $\rightarrow$ 5/2	-1.85	4.2×10^{-5}	1.0×10^{-4}	36.3	90.0	--	--
9/2 $\rightarrow$ 5/2	+0.034	--	--	47.3	118.0	245	617
9/2 $\rightarrow$ 5/2	+9.0	--	--	0.574	1.44	2.26×10^5	5.63×10^7

The E1 and M1 values are much too inhibited for the 5/2 to 5/2 transition while the E2 and M2 values are typical; this means that the transition is most likely 9/2 to 5/2. The E2 value for $\delta = .034$ is closer to the average of 10 than the value for $\delta = 9.0$ by a factor of two. Although the M2 value for $\delta = 9.0$ is typical the enhancement of the E3 and M3 part is unreasonable and does not agree with the few known examples. This analysis favors a transition of $9/2^+$ to $5/2^+$ with an E2-M3 mixing ratio of $\delta = 0.034$ for the 2.52 MeV gamma ray.

This final analysis yields



The spins of the first two excited states have been fixed beyond reasonable doubt by several experiments including this one. The spin and parity of the 2.87 MeV level had not been measured prior to this experiment, although Bent and co-workers (Be 63) inferred from their lifetime measurements and branching ratios that the level has spin $9/2$ and Howard and co-workers (Ho 65) concluded that the level must have spin $\geq 5/2$ because of the high decay rate to the $7/2^+$ level. This experiment indicates that the spin of this level is most probably $9/2$ with positive parity.

The E2/M1 mixing ratio of the 0.35 MeV gamma ray measured in this experiment is higher than previously reported values. Deuchars and Dandy (De 61) found it to be in the range $+0.004 < \delta < +0.03$. They assumed that the state was formed by s wave neutron emission from a 2^+ state in Ne^{22} . Since their experiment was reported, Powers and co-workers (Po 64) have shown that level to be 1^- by the elastic scattering of alpha particles from O^{18} . This means that neutrons leaving Ne^{22} must have odd angular momentum if the 0.35 MeV level in Ne^{21} has positive parity. There may then have been a small contribution to the correlation from $m = \pm 3/2$ substates, resulting in a lower value of δ . Howard and co-workers (Ho 65) find $\delta_{0.35} = +0.005 \pm 0.025$ and $\delta_{1.40} = +0.14 \pm 0.03$ which are lower than the value measured in this experiment; no obvious reason for the slight discrepancy exists. Pelte and co-workers found $\delta_{1.40} = +0.11 \pm 0.04$ which is based on Deuchar and Dandy's value of $\delta_{0.35} = +0.02$ in a

gamma-gamma correlation. The values found in this experiment are averages based on three separate types of correlation experiments, all of which agree closely. No value for $\delta_{1.75}$ has been reported other than $\delta_{1.75} = +0.03 \pm 0.04$ from this experiment.

The branching ratio for the 1.75 MeV level, expressed as

$\frac{\Gamma_{1.75}}{\Gamma_{1.75} + \Gamma_{1.40}}$, was measured to be 0.06 by (Pe 60), 0.07 ± 0.01 by (Ho 65), 0.10 by (Be 63), and 0.045 ± 0.015 in this experiment.

These are in reasonable agreement. No mixing ratios have been reported for the 1.12 MeV transition and 2.52 MeV transition other than the measurements described in this thesis. The branching ratio expressed as $\frac{\Gamma_{1.12}}{\Gamma_{1.12} + \Gamma_{2.52}}$ has been measured by (Pe 64) to be ≥ 0.50 and (Be 63) to be 0.7 which is not contradictory to a value of ≥ 0.37 measured in this experiment.

The single particle model has not been able to produce large enough E2 partial radiative widths and quadrupole moments. A larger quadrupole moment could be generated if many charged particles participate in some collective motion such as a rotating core. It is assumed that closed shell nuclei are essentially spherical in shape and the nucleons outside closed shells might be capable of polarizing the core, giving rise to stable non-spherical shapes. These non-spherical shapes may give rise to rotational spectra which are modified by the coupling of the extra nucleons. Versions of this type of model employing strong coupling between the particle and the

core have had considerable success recently in correlating the experimental data to a theoretical interpretation. One of these models, the Nilsson "unified" model (Ni 55), has been used by Freeman (Fr 60) for Ne^{21} and by Paul and Montague (Pa 58) for Na^{23} .

Assuming a prolate core for Ne^{21} , Freeman has generated a spectrum in good agreement with experiment. It is based on the identification of $K^\pi = 3/2^+$ rotational band as starting at the $3/2^+$ ground state. Figure 3-48 illustrates the results of Freeman. Since the 2.80 MeV level has been found to be $1/2^+$ in spin and parity, it suggests a mixing of $K^\pi = 1/2^+$ rotational band head. She considers a $K^\pi = 5/2^+$ band head as starting in this region in order to produce the proper mixing of the states for a better agreement in the energy of the levels. The level at 2.87 MeV may be the start of this $K^\pi = 5/2^+$ band head, but as has been shown by the experiment, is more likely a $9/2^+$ level based on the $3/2^+$ band head. Bent and co-workers (Be 63) have used this model to calculate wave functions and transition probabilities to compare to their measured values. The following table was derived from their work and that of (Kh 59) to indicate the degree of success enjoyed by this model. (Widths in eV)

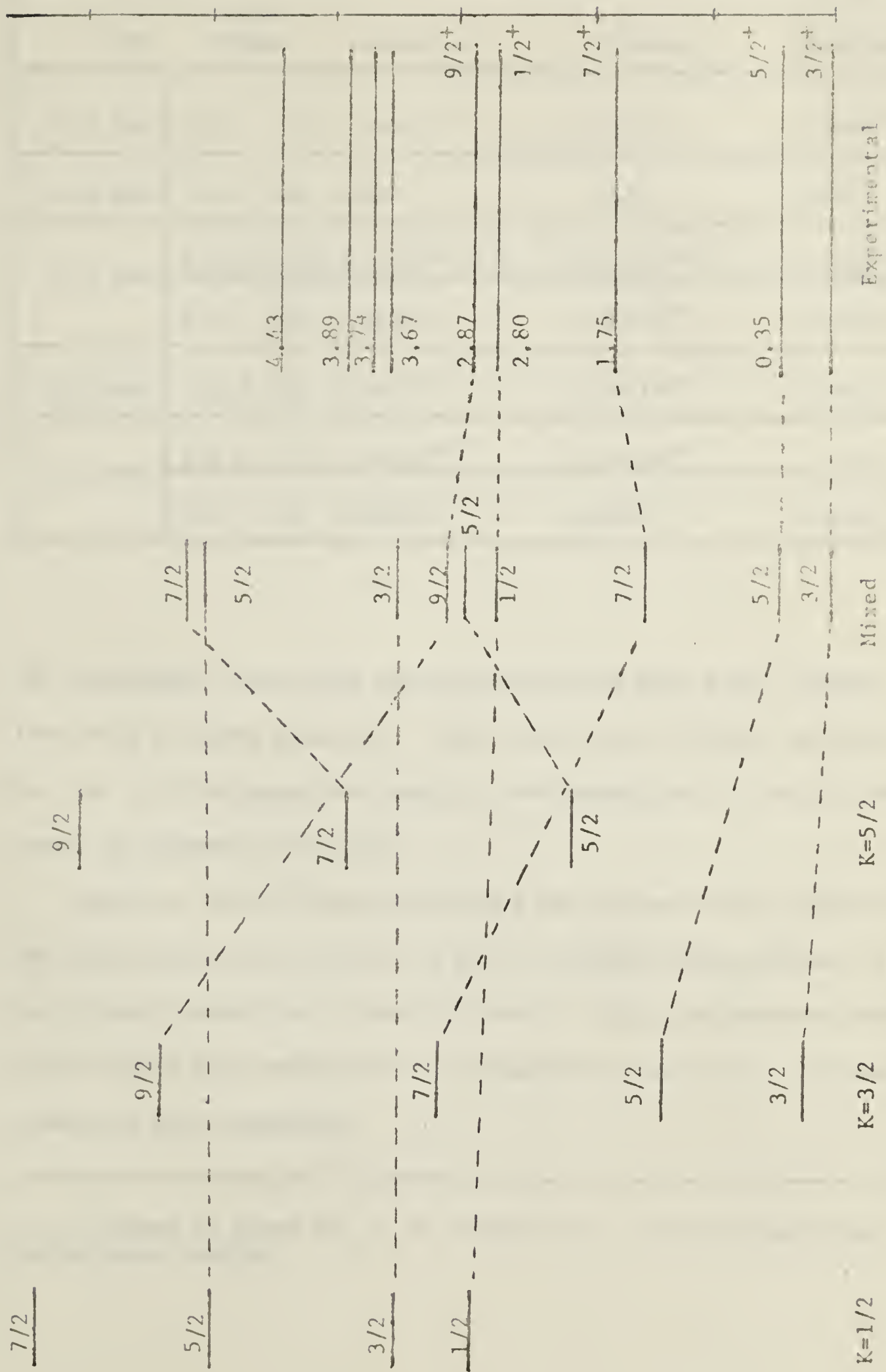


FIG. 3-48 ENERGY LEVELS OF ^{221}Po .

γ ray	Spin Change	Measured	Nilsson	Weisskopf
0.35 MeV	$5/2 \rightarrow 3/2$	1.06×10^{-5}	2.2×10^{-4}	0.9×10^{-3}
1.40 MeV	$7/2 \rightarrow 5/2$	0.006	0.02	0.057
1.12 MeV	$5/2 \rightarrow 7/2$	3.3×10^{-3}	1.32×10^{-4}	2.9×10^{-2}
	$9/2 \rightarrow 7/2$	3.3×10^{-3}	1.32×10^{-2}	2.9×10^{-2}
1.75 MeV	$7/2 \rightarrow 3/2$	2.5×10^{-4}	0.66×10^{-4}	4.8×10^{-5}
2.52 MeV	$5/2 \rightarrow 5/2$	1.42×10^{-3}	1.58×10^{-2}	3.36
	$9/2 \rightarrow 5/2$	1.42×10^{-3}	3.3×10^{-3}	3.0×10^{-5}

The calculated transition probabilities from this model compare favorably to those measured. Note that there is better agreement for the 1.12 MeV gamma ray and 2.52 MeV gamma ray if the 2.87 MeV level is assumed to be $9/2^+$.

Bernier (Be 65)* has applied the SU_3 nuclear shell model to the interpretation of levels in Ne^{21} , assuming five nucleons in the 2s-1d shell beyond the closed O^{16} shell. Using preliminary parameter values which have worked well in neighboring nuclei his calculation gives the level sequence.

*I wish to thank Dr. J. P. Bernier for communicating these preliminary results.

MeV	J
3.11	11/2
2.14	1/2
2.11	3/2
1.91	9/2
1.21	7/2
0.45	5/2
0	3/2

These results can be modified considerably by reasonable adjustment of the parameter values; no such adjustment has been made in the above. With the more adequate experimental data now available, a more detailed calculation with this model is worthwhile.

The above models and others have been successful in correlating some of the available experimental data. As more experimental facts are uncovered, conclusions regarding the merits of the different models and consequently the structure of Ne^{21} and similar nuclei will become clearer.

The first part of the paper is devoted to a general discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The second part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The third part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one.

The fourth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The fifth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one.

The sixth part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one. The seventh part of the paper is devoted to a detailed discussion of the problem of the origin of life. It is shown that the problem is not only a scientific one, but also a philosophical one.

APPENDIX A

The equations in this Appendix are the predicted angular distributions derived from equation 2.3 on page 13.

When J is $1/2$ the predicted distribution is isotropic, for K cannot be greater than zero. This is because of the triangular condition demanding $K \leq |J| + |J|$ and the requirement that K be even or zero.

(A-1) $3/2 \rightarrow 1/2$

$$\begin{aligned} W(\theta) = & (1 + \delta^2)[P(1/2) + P(3/2)] + \{[-.5P(1/2) + .5P(3/2)] \\ & + [-1.732P(1/2) + 1.732P(3/2)]\delta + [+ .5P(1/2) - .5P(3/2)]\delta^2\} \\ & \times Q_2P_2(\cos \theta) \end{aligned}$$

(A-2) $3/2 \rightarrow 3/2$

$$\begin{aligned} W(\theta) = & (1 + \delta^2)[P(1/2) + P(3/2)] + \{[.4P(1/2) - .4P(3/2)] \\ & + [-1.55P(1/2) + 1.55P(3/2)]\delta + [+ .5P(1/2) - .5P(3/2)]\delta^2\} \\ & \times Q_2P_2(\cos \theta) \end{aligned}$$

(A-3) $3/2 \rightarrow 5/2$

$$W(\theta) = (1 + \delta^2)[P(1/2) + P(3/2)] + \{[-.1P(1/2) + .1P(1/2)] \\ + [1.183P(1/2) - 1.183P(3/2)]\delta + [.357P(1/2) - .357P(3/2)]\delta^2\} \\ \times Q_2P_2(\cos \theta)$$

(A-4) $3/2 \rightarrow 7/2$

$$W(\theta) = (1 + \delta^2)[P(1/2) + P(3/2)] + \{[+.142P(1/2) - .142P(3/2)] \\ + [.925P(1/2) - .925P(3/2)]\delta + [-.5P(1/2) + .5P(3/2)]\delta^2\} \\ \times Q_2P_2(\cos \theta)$$

(A-5) $5/2 \rightarrow 3/2$

$$W(\theta) = (1 + \delta^2)[P(1/2) + P(3/2) + P(5/2)] + \{[-.4P(1/2) - .094P(3/2) \\ + .496P(5/2)] - [2.02P(1/2) - .479P(3/2) + 2.5P(5/2)]\delta \\ + [.204P(1/2) + .048P(3/2) - .252P(5/2)]\delta^2\} Q_2P_2(\cos \theta) \\ + \{.651P(1/2) - .976P(3/2) + .325P(5/2)\}\delta^2 Q_4P_4(\cos \theta)$$

(A-6) $5/2 \rightarrow 5/2$

$$W(\theta) = (1+\delta^2)[P(1/2) + P(3/2) + P(5/2)] + \{[.457P(1/2) + .114P(3/2) - .571P(5/2)] \\ + [-1.083P(1/2) - .27P(3/2) + 1.354P(5/2)]\delta + [-.204P(1/2) \\ -.051P(3/2) + .255P(5/2)]\delta^2\} Q_2P_2(\cos \theta) + [-.367P(1/2) \\ + .551P(3/2) - .1836P(5/2)]\delta^2 Q_4P_4(\cos \theta)$$

(A-7) $5/2 \rightarrow 7/2$

$$W(\theta) = (1+\delta^2)[P(1/2) + P(3/2) + P(5/2)] + \{[-.143P(1/2) - .035P(3/2) \\ + .178P(5/2)] + [1.483P(1/2) + .371P(3/2) - 1.854P(5/2)]\delta \\ + [-.347P(1/2) - .081P(3/2) + .433P(5/2)]\delta^2\} Q_2P_2(\cos \theta) \\ + [+ .109P(1/2) - .163P(3/2) + .054P(5/2)]\delta^2 Q_4P_4(\cos \theta)$$

(A-8) $7/2 \rightarrow 3/2$

$$W(\theta) = (1+\delta^2)[P(1/2) + P(3/2) + P(5/2) + P(7/2)] \\ + \{[.505P(1/2) + .305P(3/2) - .101P(5/2) - .711P(7/2)] \\ - [1.1P(1/2) + .66P(3/2) - .22P(5/2) - 1.539P(7/2)]\delta \\ + [.592P(1/2) + .355P(3/2) - .118P(5/2) - .83P(7/2)]\delta^2\} Q_2P_2 \\ - \{[.365P(1/2) - .121P(3/2) - .529P(5/2) + .284P(7/2)] \\ + [1.97P(1/2) - .654P(3/2) - 2.86P(5/2) + 1.54P(7/2)]\delta \\ + [.019P(1/2) - .006P(3/2) - .027P(5/2) + .015P(7/2)]\delta^2\} Q_4P_4$$

(A-9) $7/2 \rightarrow 5/2$

$$\begin{aligned} W(\theta) = & (1+\delta^2)[P(1/2) + P(3/2) + P(5/2) + P(7/2)] \\ & + \{ [-.325P(1/2) - .194P(3/2) + .064P(5/2) + .45P(7/2)] \\ & + [-2.05P(1/2) - 1.228P(3/2) + .409P(5/2) + 2.86P(7/2)] \delta \\ & + [.083P(1/2) + .05P(3/2) - .016P(5/2) - .117P(7/2)] \delta^2 \} Q_2 P_2 \\ & + [.645P(1/2) + .214P(3/2) - 1.87P(5/2) + 1.01P(7/2)] \delta^2 Q_4 P_4(\cos \theta) \end{aligned}$$

(A-10) $7/2 \rightarrow 7/2$

$$\begin{aligned} W(\theta) = & [P(1/2) + P(3/2) + P(5/2) + P(7/2)](1+\delta^2) \\ & + [.476P(1/2) + .285P(3/2) - .095P(5/2) - .666P(7/2)] \\ & [-.824P(1/2) - .495P(3/2) + .165P(5/2) + 1.154P(7/2)] \delta \\ & [-.272P(1/2) - .163P(3/2) + .054P(5/2) + .381P(7/2)] \delta^2 \} Q_2 P_2(\cos \theta) \\ & + [-.489P(1/2) + .162P(3/2) + .707P(5/2) - .381P(7/2)] \delta^2 Q_4 P_4(\cos \theta) \end{aligned}$$

(A-11) $9/2 \rightarrow 5/2$

$$\begin{aligned} W(\theta) = & (1+\delta^2)[P(1/2) + P(3/2) + P(5/2) + P(7/2) + P(9/2)] \\ & + \{ [.476P(1/2) + .357P(3/2) + .119P(5/2) - .238P(7/2) - .714P(9/2)] \\ & [-1.2P(1/2) - .9P(3/2) - .3P(5/2) + .6P(7/2) + 1.8P(9/2)] \delta \\ & [.454P(1/2) + .34P(3/2) + .113P(5/2) - .227P(7/2) - .681P(9/2)] \delta^2 \} Q_2 \\ & \times P_2(\cos \theta) \\ & + \{ [-.285P(1/2) - .047P(3/2) + .27P(5/2) + .35P(7/2) - .286P(9/2)] \\ & [-1.8P(1/2) - .3P(3/2) + 1.7P(5/2) + 2.2P(7/2) - 1.8P(9/2)] \delta \\ & [-.017P(1/2) - .003P(3/2) + .016P(5/2) + .021P(7/2) \\ & \quad - .017P(9/2)] \delta^2 \} Q_4 P_4(\cos \theta) \end{aligned}$$

(A-12) $9/2 \rightarrow 7/2$

$$\begin{aligned}
 W(\theta) = & [P(1/2) + P(3/2) + P(5/2) + P(7/2) + P(9/2)] [1 + \delta^2] \\
 & + \{ [-.333P(1/2) - .249P(3/2) - .083P(5/2) + .166P(7/2) + .5P(9/2)] \\
 & [-2.06P(1/2) - 1.544P(3/2) - .515P(5/2) + 1.029P(7/2) \\
 & + 3.089P(9/2)] \delta \\
 & [.022P(1/2) + .016P(3/2) + .005P(5/2) - .011P(7/2) - .032P(9/2)] \delta^2 \\
 & P_2(\cos \theta) \\
 & + \{ [+ .623P(1/2) + .104P(3/2) - .588P(5/2) - .762P(7/2) \\
 & + .623P(9/2)] \delta^2 \} P_4(\cos \theta)
 \end{aligned}$$

(A-13) $11/2 \rightarrow 7/2$

$$\begin{aligned}
 W(\theta) = & [P(1/2) + P(3/2) + P(5/2) + P(7/2) + P(9/2) + P(11/2)] (1 + \delta^2) \\
 & + \{ [+ .454P(1/2) + .375P(3/2) + .22P(5/2) - .013P(7/2) \\
 & - .323P(9/2) - .713P(11/2)] \\
 & [-1.246P(1/2) - 1.031P(3/2) - .604P(5/2) + .035P(7/2) \\
 & + .888P(9/2) + 1.957P(11/2)] \delta \\
 & [+ .366P(1/2) + .303P(3/2) + .177P(5/2) - .010P(7/2) \\
 & - .261P(9/2) - .575P(11/2)] \delta^2 \} Q_2 P_2 \\
 & + \{ [-.242P(1/2) - .104P(3/2) + .112P(5/2) + .285P(7/2) + .233P(9/2) \\
 & - .285P(11/2)] \\
 & [-1.663P(1/2) - .713P(3/2) + .772P(5/2) + 1.96P(7/2) \\
 & + 1.6P(9/2) - 1.96P(11/2)] \delta \\
 & [-.092P(1/2) - .039P(3/2) + .043P(5/2) + .108P(7/2) + .088P(9/2) \\
 & - .108P(11/2)] \delta^2 \} Q_4 P_4
 \end{aligned}$$

APPENDIX B

This Appendix contains the predicted Legendre polynomial coefficients for the gamma-gamma correlations derived from equation 2.4 on page 17. The coefficients are for a $7/2 \rightarrow 5/2 \rightarrow 3/2$ spin combination.

$$\begin{aligned}
 A_0^I = & P(1/2) [1.224 + .451\delta_1 + 1.127\delta_1^2 + 1.144\delta_2 + 2.29\delta_1\delta_2 + .642\delta_1^2\delta_2 \\
 & + 1.074\delta_2^2 - .022\delta_1\delta_2^2 + .958\delta_1^2\delta_2^2] + P(3/2) [1.132 + .674\delta_2 \\
 & + .817\delta_2^2 + .333\delta_1 + 1.69\delta_1\delta_2 - .1512\delta_1\delta_2^2 + 1.132\delta_1^2 \\
 & + .677\delta_1^2\delta_2 + 1.014\delta_1^2\delta_2^2] + P(5/2) [.966 - .17\delta_2 + .8\delta_2^2 \\
 & + .148\delta_1 + .751\delta_1\delta_2 - .3\delta_1\delta_2^2 + 1.067\delta_1^2 + .341\delta_2^2\delta_1 + .996\delta_2\delta_1^2] \\
 & + P(7/2) \text{ [Not calculated]}
 \end{aligned}$$

$$\begin{aligned}
 A_2^I = & P(1/2) [- .47 - .665\delta_2 - .434\delta_2^2 - 2.658\delta_1 - 3.547\delta_1\delta_2 - 1.777\delta_1\delta_2^2 - .116\delta_1^2 \\
 & - 1.001\delta_1^2\delta_2 - .082\delta_1^2\delta_2^2] + P(3/2) [- .22 - .081\delta_2 + .052\delta_2^2 \\
 & - .1567\delta_1 - 1.971\delta_1\delta_2 - 1.384\delta_1\delta_2^2 - .037\delta_1^2 - .4609\delta_1^2\delta_2 \\
 & - .011\delta_1^2\delta_2^2] + P(5/2) [+ .148 + .406\delta_2 - .1128\delta_2^2 + .263\delta_1 \\
 & - .658\delta_1\delta_2 + .559\delta_1\delta_2^2 + .173\delta_1^2 - .471\delta_1^2\delta_2 - .847\delta_1^2\delta_2^2] \\
 & + P(7/2) \text{ [Not calculated]}
 \end{aligned}$$

$$\begin{aligned} A_4^I = & P(1/2)[.805\delta_1^2 + 1.265\delta_1^2\delta_2 + .534\delta_1^2\delta_2^2] + P(3/2)[- .311\delta_1^2 - .643\delta_1^2\delta_2 \\ & - .082\delta_1^2\delta_2^2] + P(5/2)[- .794\delta_1^2 + .052\delta_1^2\delta_2 - .716\delta_1^2\delta_2^2] \\ & + P(7/2) \quad [\text{Not calculated}] \end{aligned}$$

$$\begin{aligned} A_0^{II} = & P(1/2)[1.225 + .294\delta_2 + 1.12\delta_2^2 + 1.428\delta_1 + 2.3\delta_1\delta_2 + .662\delta_1\delta_2^2 + 1.319\delta_1^2 \\ & + .785\delta_1^2\delta_2 + 1.145\delta_1^2\delta_2^2] + P(3/2)[+1.139 + .1631\delta_2 + .992\delta_2^2 \\ & + .919\delta_1 + 1.696\delta_1\delta_2 + .422\delta_1\delta_2^2 + .964\delta_1^2 + .258\delta_1^2\delta_2 \\ & + .945\delta_1^2\delta_2^2] + P(5/2)[+.148 + .753\delta_2 - .075\delta_2^2 - .129\delta_1 - .66\delta_1\delta_2 \\ & + .518\delta_1\delta_2^2 - .221\delta_1^2 - 1.124\delta_1^2\delta_2 + .135\delta_1^2\delta_2^2] + P(7/2) \quad [\text{Not calculated}] \end{aligned}$$

$$\begin{aligned} A_2^{II} = & P(1/2)[- .472 - 2.395\delta_2 + .144\delta_2^2 - .701\delta_1 - 3.56\delta_1\delta_2 - .058\delta_1\delta_2^2 - .326\delta_1^2 \\ & - 1.66\delta_1^2\delta_2 - .201\delta_1^2\delta_2^2] + P(3/2)[- .22 - 1.116\delta_2 + .136\delta_2^2 - .39\delta_1 \\ & - 1.878\delta_1\delta_2 + .161\delta_1\delta_2^2 - .15\delta_1^2 - .759\delta_1^2\delta_2 + .217\delta_1^2\delta_2^2] \\ & + P(5/2)[+.148 + .753\delta_2 - .075\delta_2^2 - .129\delta_1 - .66\delta_1\delta_2 + .518\delta_1\delta_2^2 \\ & - .221\delta_1^2 - 1.124\delta_1^2\delta_2 + .135\delta_1^2\delta_2^2] + P(7/2) \quad [\text{Not calculated}] \end{aligned}$$

$$\begin{aligned} A_4^{II} = & P(1/2)[.637\delta_2^2 + .441\delta_1\delta_2^2 - .028\delta_1^2\delta_2^2] + P(3/2)[- .507\delta_2^2 + .343\delta_1\delta_2^2 \\ & + .222\delta_1^2\delta_2^2] + P(5/2)[- .353\delta_2^2 - .373\delta_1\delta_2^2 + .341\delta_1^2\delta_2^2] \\ & + P(7/2) \quad [\text{Not calculated}] \end{aligned}$$

APPENDIX C

SOLID ANGLE CORRECTIONS FOR THE GAMMA RAY COUNTERS

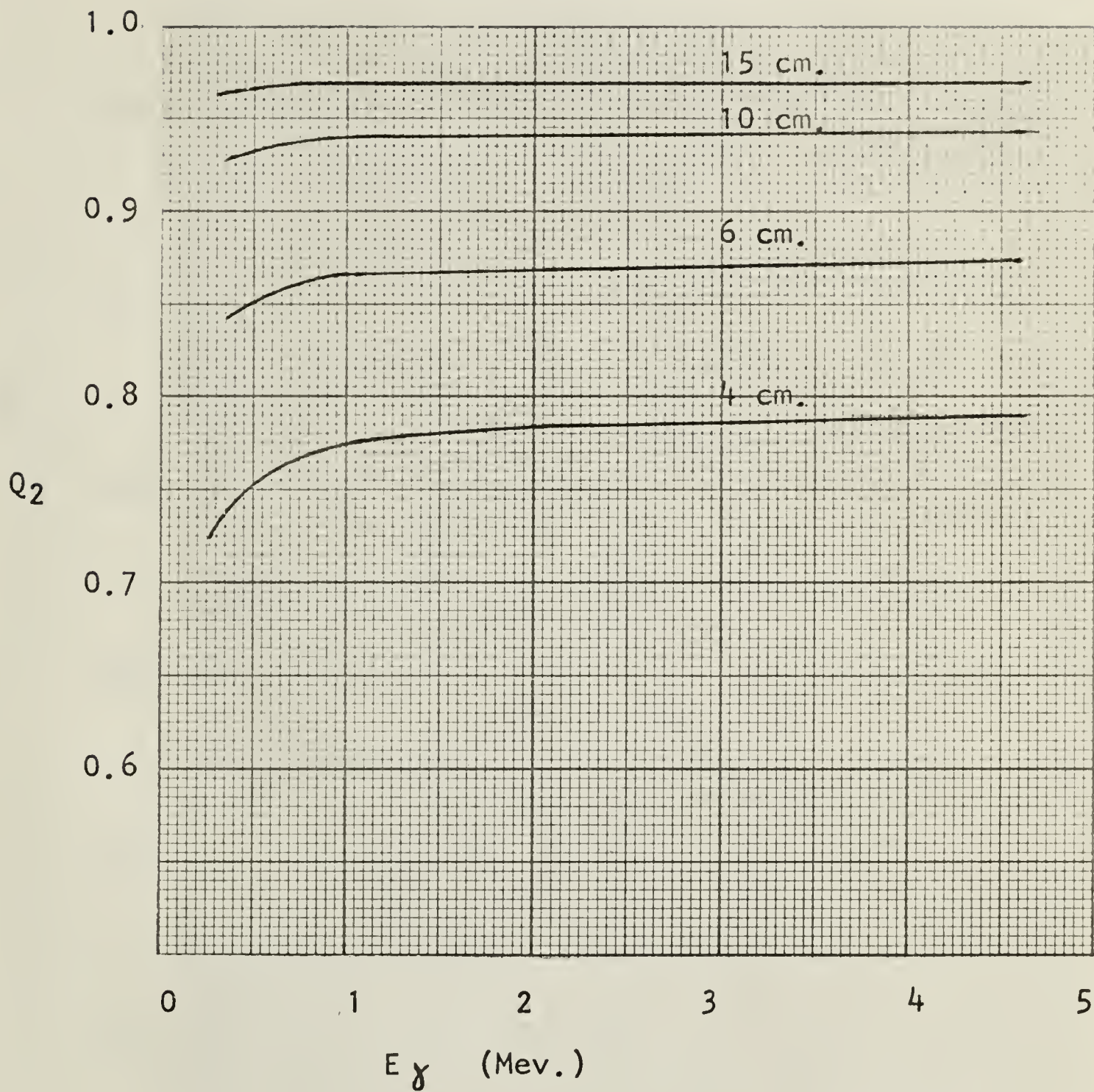


FIG. C-1 ANGULAR CORRELATION FACTORS, Q_2 , FOR A 3''X3'' NaI CRYSTAL.

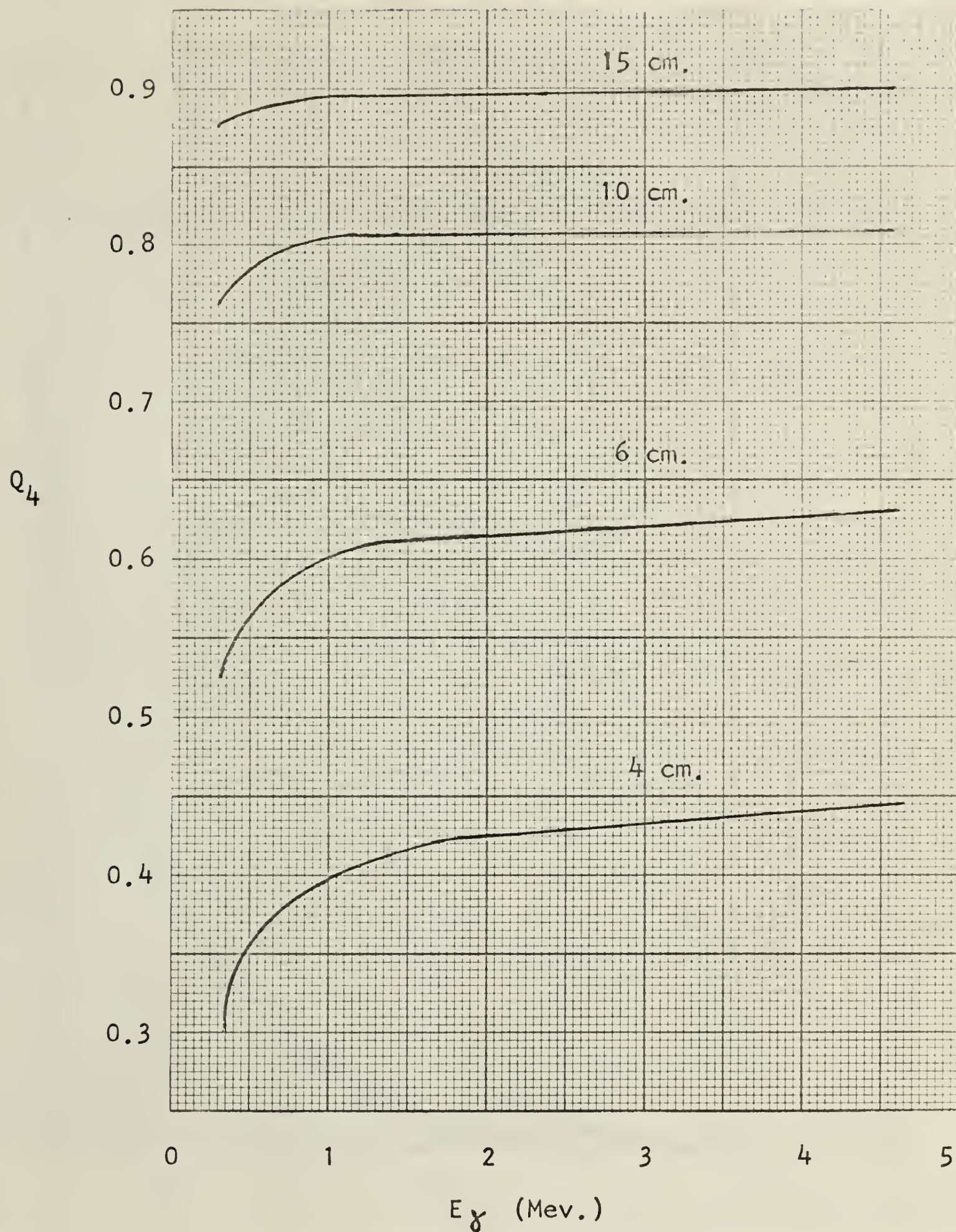


FIG. C-2 ANGULAR CORRELATION CORRECTION FACTORS, Q_4 , FOR A 3"X3" NaI CRYSTAL.

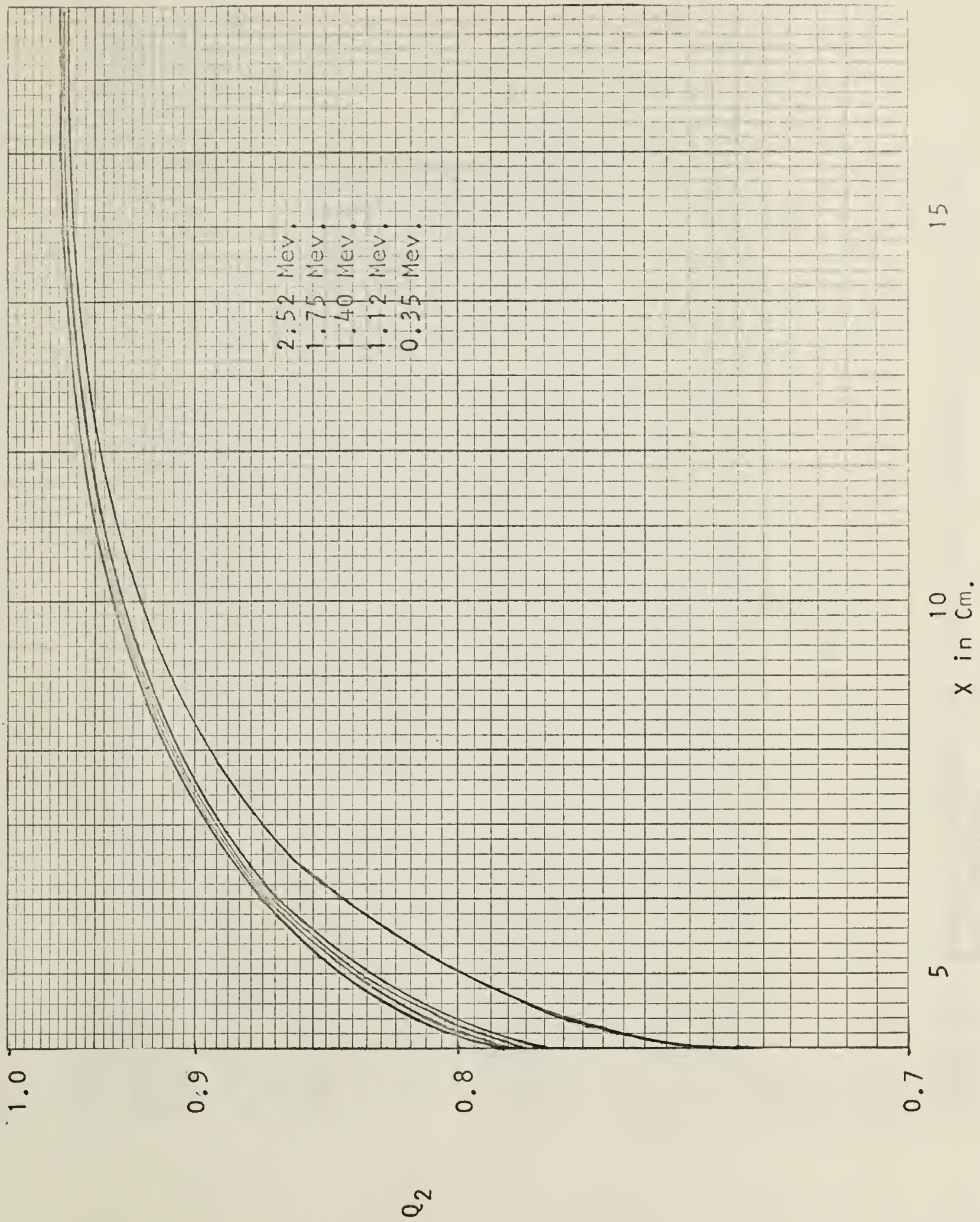


FIG. C-3 ANGULAR CORRELATION CORRECTION FACTORS, Q_2 , FOR A 3"X3" NaI CRYSTAL.

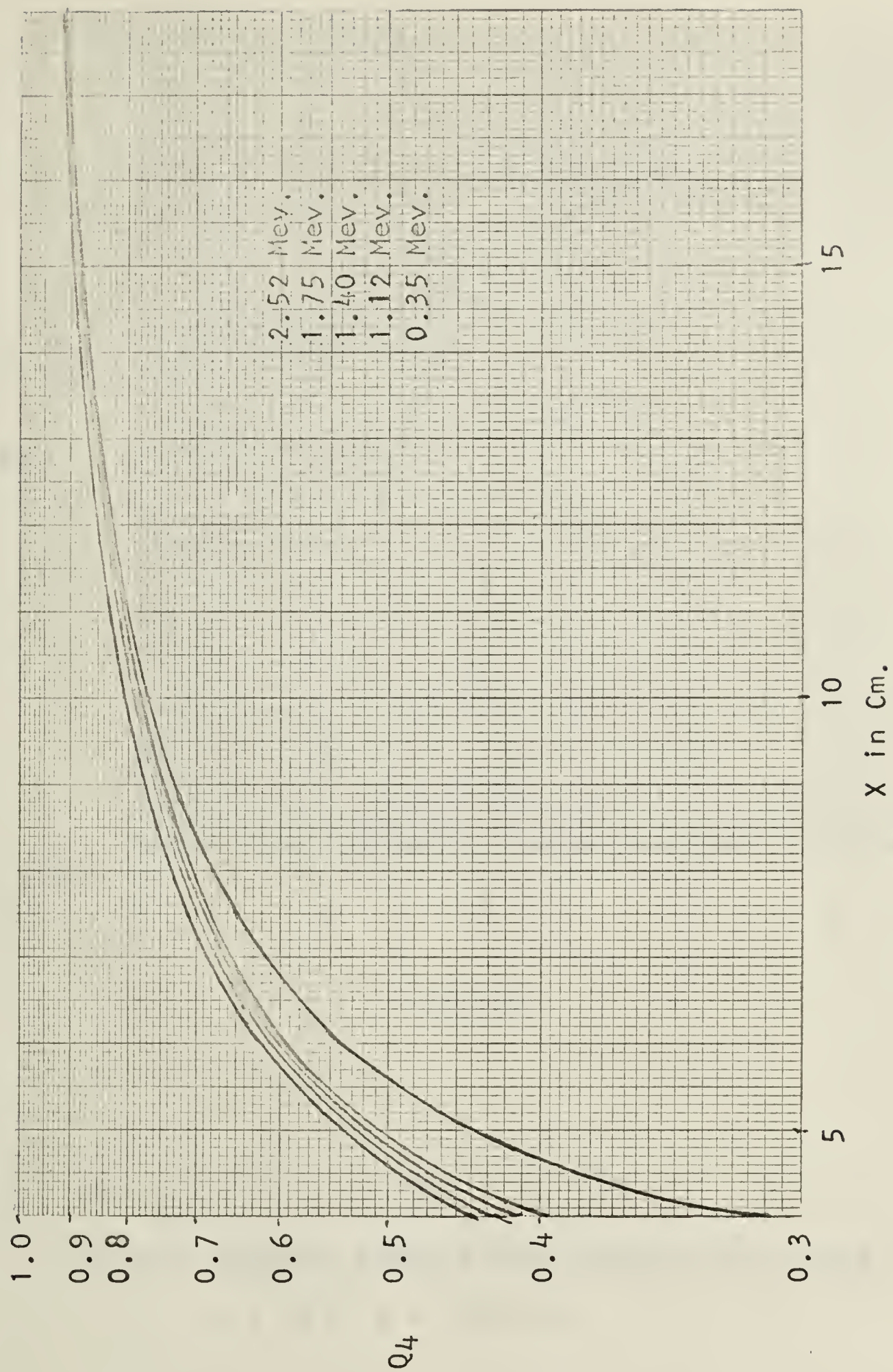


FIG. C-4 ANGULAR CORRELATION CORRECTION FACTORS, Q_4 , FOR A 3"X3" NaI CRYSTAL.

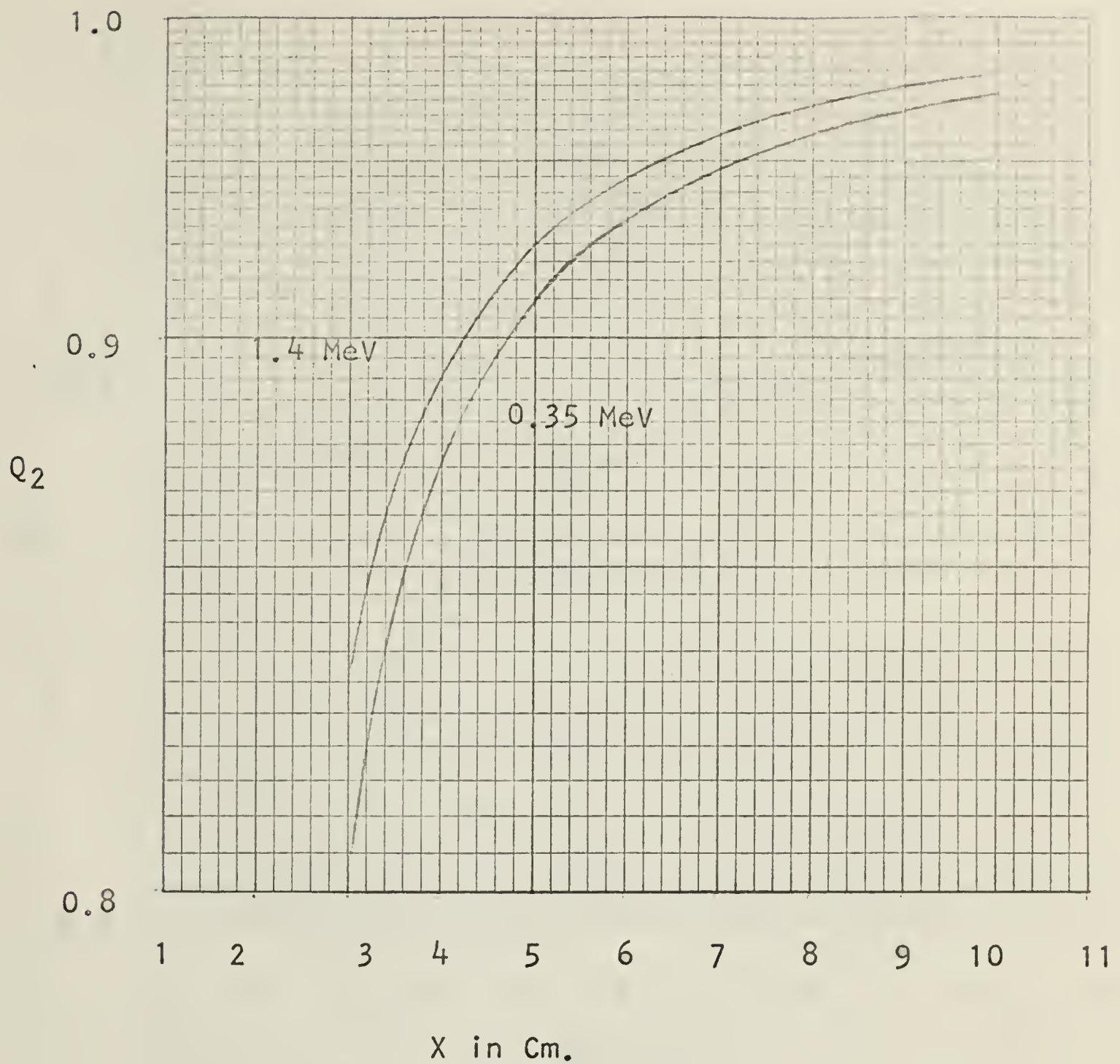


FIG. C-5 ANGULAR CORRELATION CORRECTION FACTORS, Q_2 , FOR
A 1 3/4" X 2" CRYSTAL.

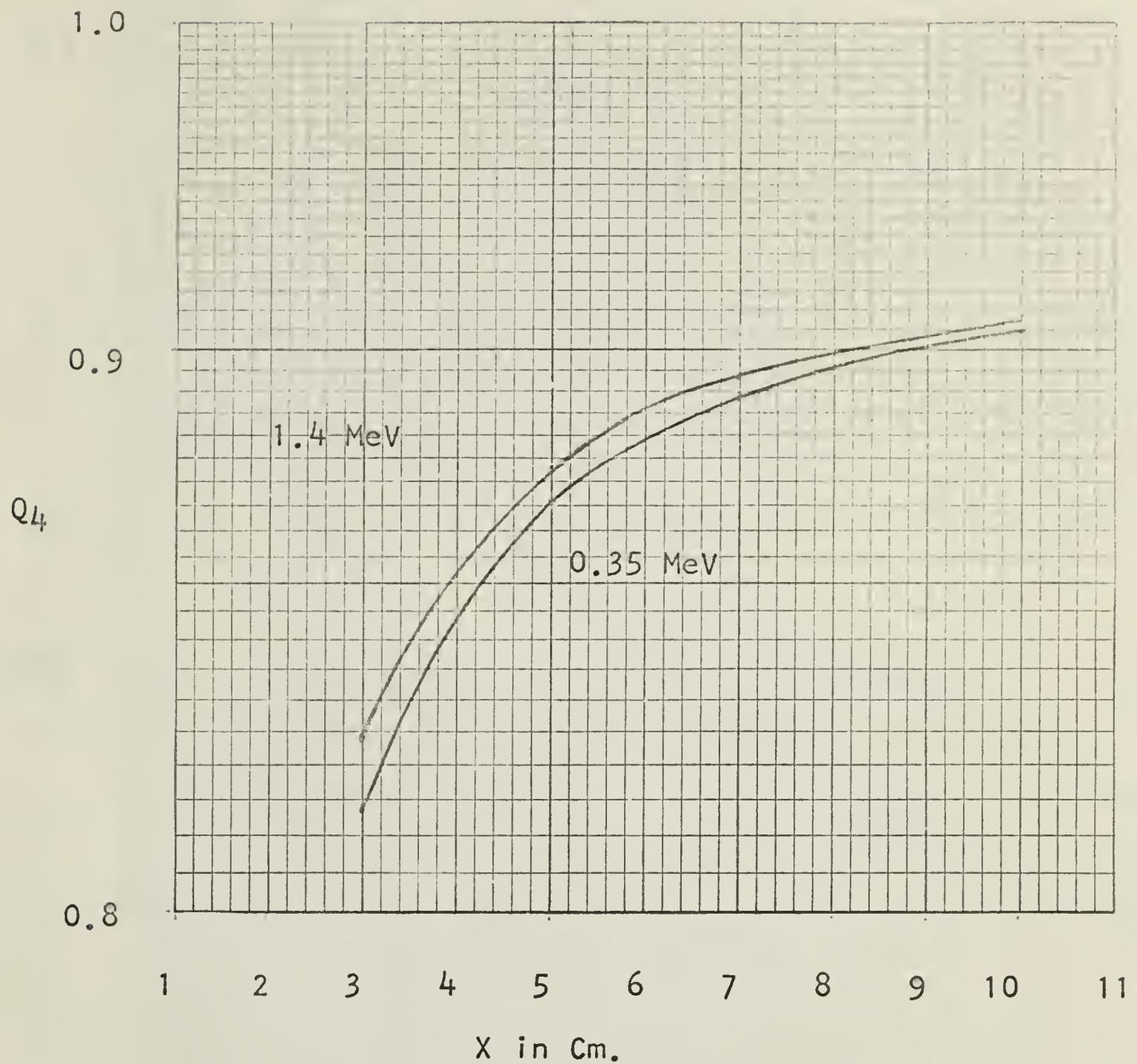


Fig. C-6 ANGULAR CORRELATION CORRECTION FACTORS, Q_4 , FOR
A 1 3/4" X 2" CRYSTAL.

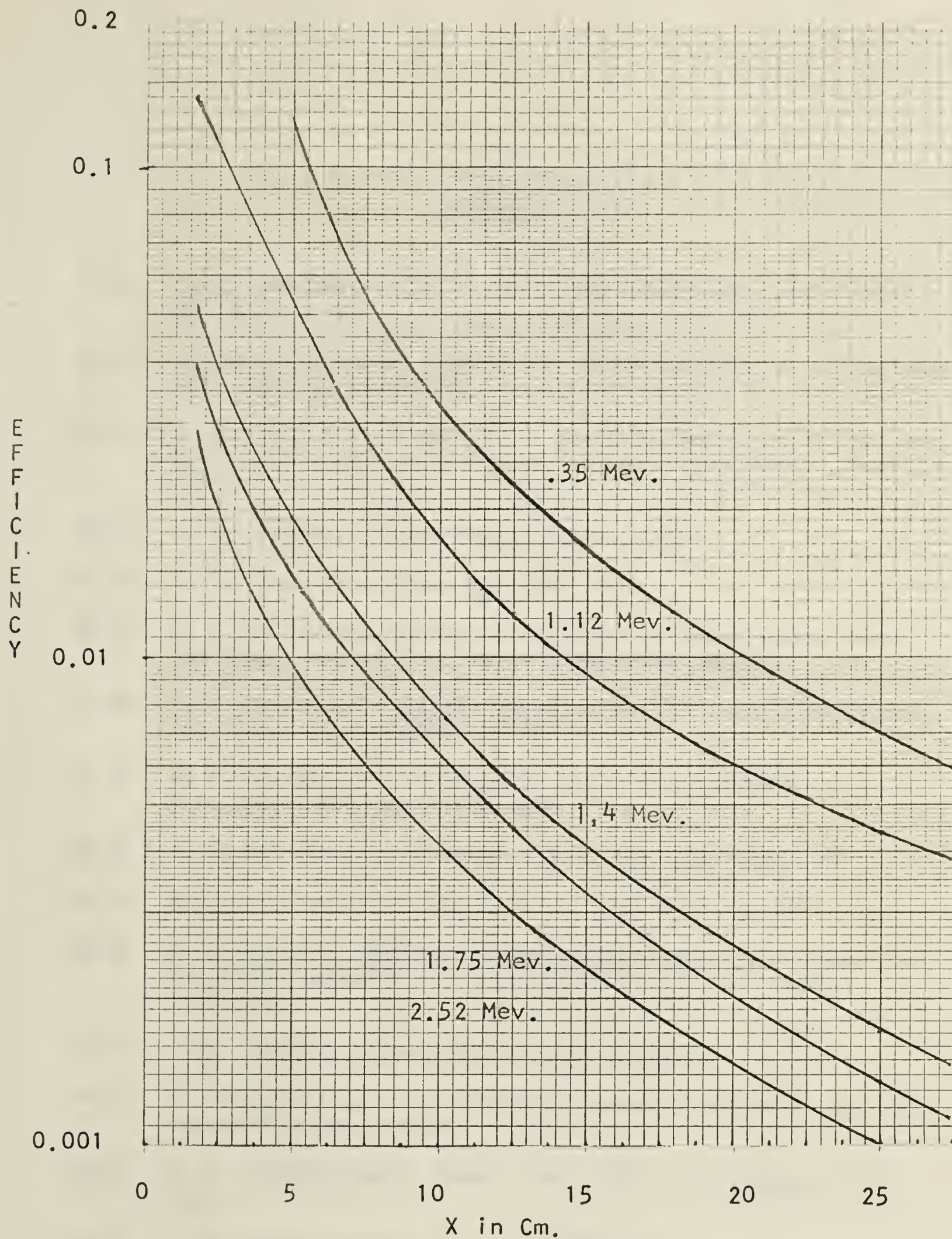


FIG. C-7 THE ABSOLUTE PHOTOPEAK EFFICIENCY VERSUS CRYSTAL DISTANCE FOR A 3"X3" NaI CRYSTAL.

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